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Hydrology and Earth System Sciences
Discussions

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

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Abstract Water resources infrastructure is critical for energy and food security, however, the development of large-scale infrastructure, such as hydropower dams, may significantly alter downstream flows, potentially leading to water resources management conflicts and disputes, especially in transboundary river basins. Mutually agreed upon water sharing policies for the operation of existing or new reservoirs is one of the most effective strategies to mitigate conflict, yet this is a complex task involving the estimation of available water, identification of users and demands, procedures for water sharing, etc. We propose a water-sharing policy framework that incorporates reservoir operating rules optimization based on conflicting uses and natural hydrologic variability, specifically tailored to drought conditions. We first establish the trade-off between downstream and upstream water availability utilizing multi-objective optimization of reservoir operating rules. Next, we simulate reservoir operation with the candidate (optimal) rules, evaluate their performance, and select the most suitable rules for balancing water uses. Subsequently, we build a relationship between the reservoir operations simulated from the selected rules and drought-specific conditions to derive water-sharing policies. Finally, we re-optimize the reservoir

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operating rules to evaluate the effectiveness of the drought-specific water sharing policies. We apply the framework to reservoir operation of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River. We find that the derived water sharing policy can balance GERD power generation and downstream releases, especially in dry conditions, effectively sharing the hydrologic risk in inflow variability among riparian countries. The proposed framework offers a robust approach to inform water sharing policies for sustainable management of transboundary water resources.

Keywords: Reservoir operation; Water sharing policy; Drought mitigation; Multi-objective optimization; Grand Ethiopian Renaissance Dam.

1. Introduction

Rapid population growth and socio-economic development exacerbate stress on the management of water resources globally (Vörösmarty et al., 2000;WWAP, 2019). Surface-water reservoirs and their effective management is one of the most efficient means to reduce this stress by reallocating water resources spatially and temporally (Gaudard et al., 2014). Thus in recent decades, many models and strategies have been investigated to inform and improve reservoir operation decision-making (Lerma et al., 2015;Chaves and Chang, 2008;Cancelliere et al., 2002;Giuliani et al., 2015a;Herman and Giuliani, 2018;Karamouz and Houck, 1982;Consoli et al., 2008;Giuliani et al., 2014;Oliveira and Loucks, 1997). In general, reservoir decisions (e.g., water releases and power generation) are determined using reservoir operating rules with available input variables including reservoir state (e.g., reservoir water level) and hydrological conditions (e.g., reservoir inflow) (Oliveira and Loucks, 1997).

Reservoir operating rules are typically derived using fitting-based and simulation-optimization-based approaches. In fitting-based rules derivation, reservoir operation decisions are optimized and subsequently fitted with input variables using linear regression (Bhaskar and Whitlatch Jr, 1980), artificial neural networks (Cancelliere et al., 2002), fuzzy inference (Chang and Chang, 2001), and decision trees (Wei and Hsu, 2008). For example, Karamouz and Houck (1982) developed annual and monthly reservoir operating rules by regressing reservoir releases optimized from deterministic dynamic programing onto reservoir decision-making state variables. Cancelliere et al. (2002) derived the operating rules of an irrigation supply reservoir by using neural networks techniques and found that the rules can improve reservoir operation performance during drought conditions. Goyal et al. (2013) compared the performance of artificial neural networks, fuzzy logic, and decision tree algorithms for deriving the operating rules of an irrigation and power supply reservoir in northern India. In simulation-optimization methods, the parameters of reservoir operating rules are optimized with an iterative simulation-based search algorithm in which the performance is evaluated directly from reservoir operation simulations (Le Ngo et al., 2007;Rani and Moreira, 2010). For example, Giuliani et al. (2015a) approximated reservoir operating rules by using artificial neural networks and radial basis functions (RBFs) and optimized the rules for multi-purpose water reservoirs with an evolutionary algorithm.

Most of these approaches are implemented in water resources systems contained within a basin or jurisdiction in which the benefits (e.g. power generation, water supply, and ecosystem function maintenance) can be quantified and evaluated (Reddy and Nagesh Kumar, 2007;Feng et al., 2018;Yang et al., 2016). Reservoir operations in transboundary river basins are necessarily more complex given a wide variety of social, political, economic, cultural, and physiographic conditions (Zeitoun and Mirumachi, 2008). Disputes and conflicts are not uncommon between riparian states in transboundary river basins when water sharing agreements are non-existent or non-enforceable and claims may be defined based on historical use. For example, the Nile River serves eleven countries, 250 million people (Nile Basin Initiative, 2017), and is vital to agriculture, industry, and hydropower, (Paisley and Henshaw, 2013), yet no mutually agreed upon water sharing policies exist. (The 1959 agreement (Guariso and Whittington, 1987) has been repudiated by upstream riparian states.) Acknowledging significantly divergent interests and a history of conflict and distrust, quantifying the impact of reservoir operation on downstream benefits is challenging, hindering development of water sharing strategies (Link et al., 2016).

According to the Transboundary Freshwater Dispute Database (McCracken and Wolf, 2019), the existing 310 international river basins across the world are shared by 150 countries and disputed areas, cover 45% of the Earth's land surface, and contribute to 60% of the world's freshwater resources. As suggested by Sadoff and Grey (2002), it is critical to understand and account for the range of inter-related benefits resulting from the development of international rivers in a cooperative way. Such cooperation of water resources development in international river basins has been widely investigated in recent years (Li et al., 2019;Luchner et al., 2019;Anghileri et al., 2013;Uitto and Duda, 2002;Dombrowsky, 2009;Tilmant and Kinzelbach, 2012;Arjoon et al., 2016;Wu and Whittington, 2006;Wheeler et al., 2018;Goor et al., 2010;Degefu et al., 2016). 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; Li et al. (2019) analyzed the water benefits of stakeholders from transboundary cooperation under different reservoir operation scenarios by using cooperative game theory methods; Luchner et al. (2019) simulated reservoir operations and water allocation in an international river basin in Central Asia and found that international cooperation in the power sector can ease the conflict between upstream hydropower production and downstream irrigated agriculture.

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, there is no standard that regulates how the benefits of water use from various sectors (e.g., drinking, agriculture, industry, recreation, and navigation) are quantified and what mechanism should be used to allocate/share the benefits (Arjoon et al., 2016;Acharya et al., 2020). Thus, most previous studies focus on evaluating the impact of cooperative operation in transboundary river basins and illustrating the importance of a cooperative strategy through water system optimization and simulation (Goor et al., 2010;Anghileri et al., 2013;Uitto and Duda, 2002;Dombrowsky, 2009;Tilmant and Kinzelbach, 2012;Luchner et al., 2019). There is less literature, however, addressing strategies for reaching an agreement or consensus on water resources development amongst downstream and upstream riparian countries in transboundary river basins (Wheeler et al., 2016;Li et al., 2019;Degefu et al., 2016).

In this study, we propose a systemic framework to derive operational reservoir water-sharing policies using multi-objective optimization for water use conflict mitigation. Specifically, we (1) optimize reservoir operating rules and establish trade-off between downstream and upstream water availability, (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 forecasts, and (4) re-optimize reservoir operating rules incorporating derived water-sharing policies to evaluate effectiveness and performance. We select the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia to demonstrate the framework and illustrate how operational water-sharing strategies, reflective of upstream and downstream demands and natural hydrologic variability, can promote water-sharing agreements between upstream and downstream countries.

2. Study Area and Data

2.1. The Blue Nile Basin and the Grand Ethiopian Renaissance Dam

The Blue Nile River, the largest tributary of the Nile River, originates at Tana Lake in Ethiopia and merges with the White Nile River in Khartoum, Sudan. Average annual rainfall in the upper part of the basin varies between 1200 and 1800 mm (Conway, 2000), with a dominant rainy season in June–September contributing approximately 70% of mean annual precipitation. During this season, the Blue Nile contributes nearly 80% of the total Nile River streamflow (Swain, 2011) and the average annual runoff of the Blue Nile at Roseries, near the Ethiopia–Sudan border, is approximately 49 km^3 (Wheeler et al., 2016), thus it plays a significant role in livelihood and development in Ethiopia, Sudan and Egypt.

Ethiopia started constructing the Grand Ethiopian Renaissance Dam (GERD) across the Blue Nile River in 2011, approximately 15 km upstream of the Sudanese border (Fig. 1). When completed, the GERD will become the largest hydroelectric dam (installed capacity exceeding 5,000MW) in Africa (Government of Ethiopia, 2020) and will have a total reservoir capacity of 74 billion cubic meters. The GERD is expected to produce an average of 15,130 GWh of electricity annually (Tan et al., 2017), which will contribute to Ethiopia's national energy grid and feed the East African power pool (Nile Basin Initiative, 2012). Although the GERD is primarily designed for hydropower, and thus non-consumptive, operating to maximize power generation may result in a water release schedule significantly different from the natural annual cycle, particularly considering drought periods, with implications to Sudan and Egypt. This is the crux of the current hydro-political confronting the riparian countries.

In this study, we develop GERD reservoir operation rules considering power generation and downstream water release simultaneously to mitigate upstream-downstream water use conflicts, particularly tailored to drought periods. The study investigates water-sharing (drought mitigation) policy

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derivation procedures (reservoir operation simulation and optimization, power generation and downstream water release analysis, drought mitigation policy extraction and validation) balancing GERD production and downstream flow volumes. Historical monthly inflow at El Diem gauging station (located just downstream of the GERD site) for 1965-2017 (Fig. 2) are applied.

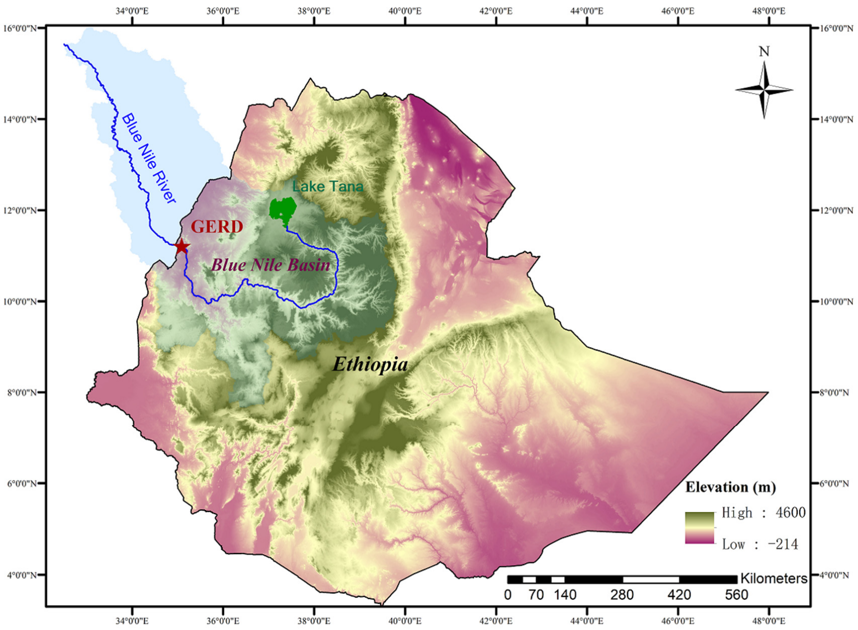

Fig. 1 Blue Nile basin with Ethiopia country borders and the location of the GERD reservoir

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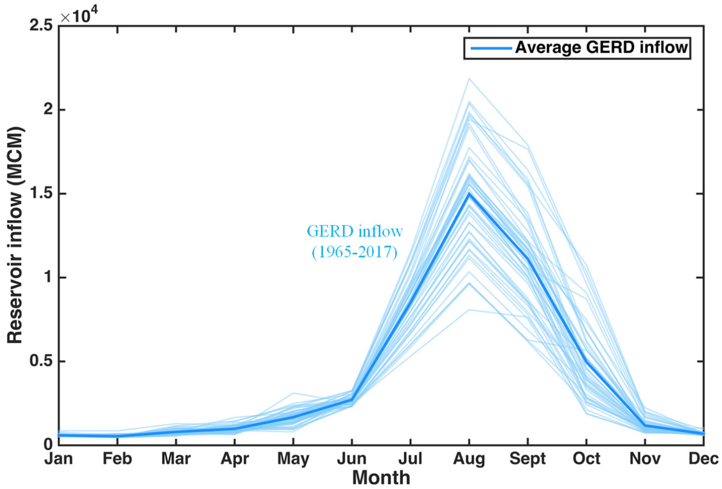

Fig. 2 Monthly inflow into the GERD reservoir during 1965-2017.

3. Models and Methods

The procedure for water sharing policy derivation and evaluation for transboundary rivers including large-scale reservoir operations is introduced in this section (Fig. 3). In summary, the process is as follows:

- First: optimize the reservoir operating rules approximated with Radial Basis Functions (RBFs) and obtain the Pareto front for upstream and downstream benefits trade-off.
- Second: select feasible solutions on the Pareto front according to the requirements of power generation and drought mitigation; specifically, for a given power generation level, the distribution of annual water release is analyzed with special attention to low flow years.
- Third: define the relationship between annual reservoir inflow and releases based on the selected feasible solutions; the policy can be further framed as a function of reservoir annual inflow predictions.
- Fourth: incorporate the policy into general RBFs-based rules to evaluate policy effectiveness and

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robustness.

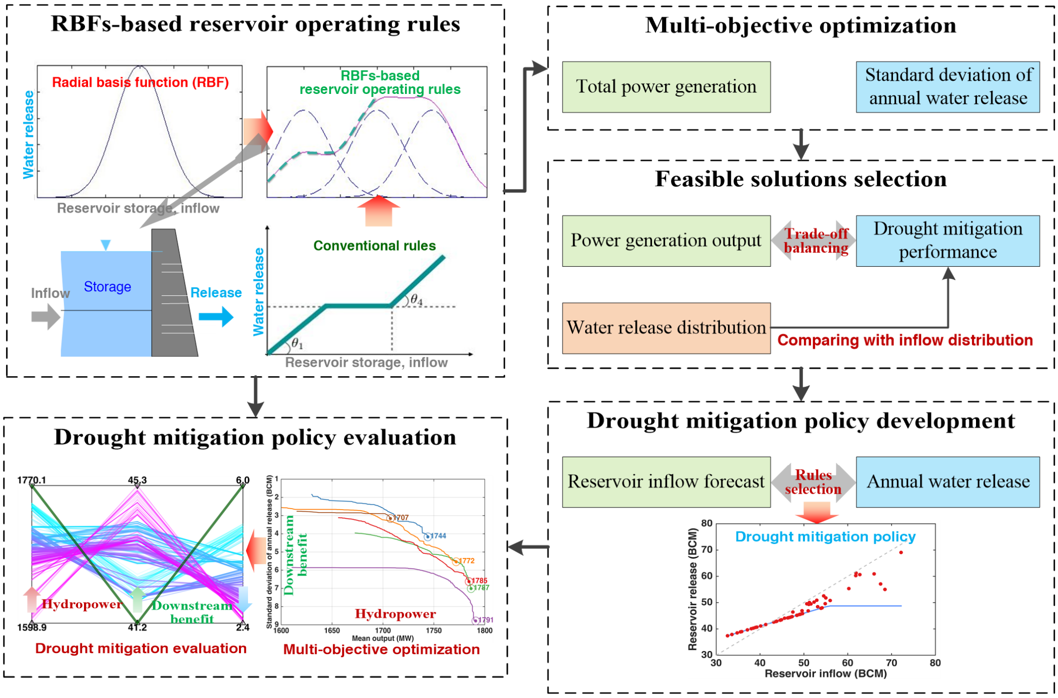

Fig. 3 Procedure of drought mitigation policy derivation and evaluation for reservoir operation in transboundary rivers.

3.1. Reservoir operation model

The primary purpose of the GERD reservoir is hydropower production; this objective function can be described as follows:

$$\mathit{Max}\quad E=\sum_{t=1}^{T}P_t\cdot\Delta t,\quad P_t=\eta\cdot g\cdot\rho\cdot Q_t^P\cdot H_t^P/1000 \qquad (1)$$

where E is hydroelectricity generation (kW h) during total number of operational periods T; P_t is the power generation output (kW) during time period t and Δt is the time (h) of a single period; η, g, and ρ

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refer to the dimensionless hydropower generation efficiency of the turbines (set as 0.9 in this study), gravitational acceleration (9.8 m/s^2), and water density (1000 kg/m^3), respectively; and Q_t^P and H_t^P are reservoir release for power generation (m^3/s) and average power head (m) in period *t*, respectively.

In lieu of modeling specific water requirements downstream of the GERD, minimizing annual water release variance is applied. This approach favors reliable releases yet also reflects natural hydrologic variability, and can be described as below.

$$Min \quad Std\left(Q_y^{out}\right) = \sqrt{\frac{\sum_{y=1}^{Y}\left(Q_y^{out} - \bar{Q}_y^{out}\right)^2}{Y}} \tag{2}$$

where Q_y^{out} is the reservoir water release 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.

Physical and operational reservoir constraints are listed as below.

(a) Water balance:

$$S_{t+1} = S_t + \left(Q_t^{in} - Q_t^{out}\right)\cdot \Delta t - EP_t \tag{3}$$

where S_t and S_{t+1} are reservoir storage (m^3) in period *t* and *t*+1, respectively, Q_t^{in} represents reservoir inflow (m^3/s) in period *t*, Q_t^{out} is reservoir release (m^3/s) in period *t*, and EP_t is the sum of evaporation and seepage from the reservoir (m^3) in period *t*.

(b) Reservoir capacity limits (Jameel, 2014):

The reservoir structural and operational constraints can be expressed as:

$$S^{\min} \leq S_t \leq S^{\max} \tag{4}$$

where $S^{\min}$ and $S^{\max}$ are the minimum and maximum allowable reservoir storage (m^3), respectively.

Additionally, S^{begin} and S^{end} represent the initial and final reservoir storage (m^3) for simulations, respectively, and are prescribed as:

$$S_t = \begin{cases} S^{begin} & t = 1 \\ S^{end} & t = T \end{cases} \tag{5}$$

(c) Reservoir release limits:

The reservoir release constraints are expressed as:

$$QL_t \leq Q_t^{out} \leq QU_t \tag{6}$$

where QL_t and QU_t are the minimum and maximum release (m^3/s) in period *t*, respectively. The expected guidelines for GERD reservoir water release are not explicitly available, thus releases are set lower than the maximum reservoir inflow during the high-flow season to reduce or eliminate downstream floods.

(d) Power generation limits (Tesfa, 2013):

$$PL_t \leq P_t \leq PU_t \tag{7}$$

where PL_t and PU_t are the minimum and maximum power limits (kW) in period *t*, respectively.

3.2. **Reservoir operating rules**

In this study, reservoir water releases are conditioned on radial basis functions (RBFs), a non-linear function approximating method (Deisenroth et al., 2013;Buşoniu et al., 2011;Giuliani et al., 2015b) which can provide universal approximation (Tikk et al., 2003) and ensure a flexible reservoir operating rules structure. For more applications of RBF models in reservoir operation see Giuliani et al. (2015a). The reservoir operating rules are defined as below.

$$Q_t^{out} = \sum_{u=1}^{U} \omega_u \varphi_u\left(X_t\right) \quad t=1,...,T \quad 0 \le \omega_u \le 1 \tag{8}$$

$$\varphi_u\left(X_t\right) = \exp\left[-\sum_{j=1}^{M} \frac{\left(\left(X_t\right)_j - c_{j,u}\right)^2}{b_u^2}\right] \quad c_{j,u} \in [-1,1], b_u \in \left(0,1\right] \tag{9}$$

where U is the number of RBFs, $\varphi(\cdot)$ and ω_u are the weights of the u^{th} RBF, M is the number of input variables X_t, and $\mathbf{c}_u$ and b_u are the M-dimensional center and radius vectors of the u^{th} RBF, respectively.

Because water release generally depends on the reservoir state (Revelle et al., 1969) and inflow, with intra- and inter-annual variability, we select reservoir storage S_t, inflow Q_t^{in}, and seasonal information τ_t (where τ_t refers to the position of the current period (month) t within a water year) as input variables and $X_t=\left(S_t, Q_t^{in}, \tau_t\right)$.

In this study, the number of RBFs is set to four (as in Giuliani et al. (2015b)), thus U=4 and M=3 (three input variables) in equation (8)-(9) resulting in 20 parameters in the RBFs-based rules. The parameters in RBFs-based rules are optimized with a simulation-optimization model (Rani and Moreira, 2010), using the Pareto-Archived Dynamically Dimensioned Search (PA-DDS) evolutionary algorithm which has been successfully applied to reservoir operating rules optimization (Yang et al., 2020). The procedure of the PA-DDS algorithm has been described in detail by Asadzadeh and Tolson (2013).

3.3. **Drought-focused water sharing policy**

To ensure downstream water supply, the GERD reservoir will need to be operated under minimum annual water release constraints. Apart from the RBFs-based rules determining the reservoir water release in each time step (months), a drought mitigation policy is also adopted to address dry periods. The policy is based on annual time steps and represented as a linear regression between annual reservoir inflow and water release. More specifically, the minimum annual reservoir water release can be determined by the following equation:

$$R_y^{\min} = \alpha \cdot Q_y^{in} + \beta + z \cdot \sigma_d \qquad (10)$$

where Q_y^{in} and $R_y^{\min}$ refer to reservoir inflow and minimum reservoir water release during year y, respectively; α and β are regression parameters estimated from simulations containing reservoir inflow values below the historical average (approximately 49 BCM). An exceedance parameter z is multiplied by the standard deviation of the regression residuals σ_d to vary how conservative the drought mitigation policy is (see Fig. 4 for a visualization of exceedance parameters). This policy design favors downstream releases under drought conditions by supplementing what would occur under natural flow conditions, however as a trade-off, the minimum reservoir release in any year will not exceed the historical average reservoir inflow (see the horizontal line in Fig. 4).

In this study, the drought mitigation policy is designed with annual streamflow data, however reservoir operating rules are derived for monthly operation. With reservoir storage in current month S_m, reservoir inflow in current month Q_m^{in}, and the predicted reservoir inflow during the rest of the year $Q_{m+1}'^{in}$, …, $Q_{12}'^{in}$, the reservoir water release in current month Q_m^{out} and the rest of year $Q_{m+1}'^{out}$, …, $Q_{12}'^{out}$ can be obtained from equations (8) and (9), thus the annual reservoir inflow and water release can be estimated as below.

$$Q_y'^{in} = \sum_1^m Q_m^{in} + \sum_{m+1}^{12} Q_m'^{in} \tag{11}$$

$$Q_y'^{out} = \sum_1^m Q_m^{out} + \sum_{m+1}^{12} Q_m'^{out} \tag{12}$$

The minimum reservoir water release in year y can be estimated from equation (10) as $R_y'^{\min}$. To ensure the minimum annual water release obligation is met, if the estimated annual reservoir water release $Q_y'^{out}$ is lower than $R_y'^{\min}$, the release in current month Q_m^{out} will be corrected according to the following:

$$Q_m^{out} = Q_m^{out} + \left(R_y'^{\min} - Q_y'^{out}\right) \times \frac{Q_m^{in}}{\sum_m^{12} Q_m'^{in}} \tag{13}$$

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 $Q_y'^{in}$ and minimum annual water release estimation $R_y'^{\min}$ will be equal to $\sum_1^{12} Q_m^{in}$ and $R_y^{\min}$, respectively. 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 inflow Q_y^{out} will be always greater than or equal to the specified minimum reservoir water release $R_y^{\min}$. In this study, both a climatology inflow forecast ($Q_t^{\prime in}$ set as the long-term average streamflow for that month) and a perfect inflow forecast ($Q_t^{\prime in}$ set to observed reservoir inflow Q_t^{in}) are used to evaluate the performance of the drought mitigation policy.

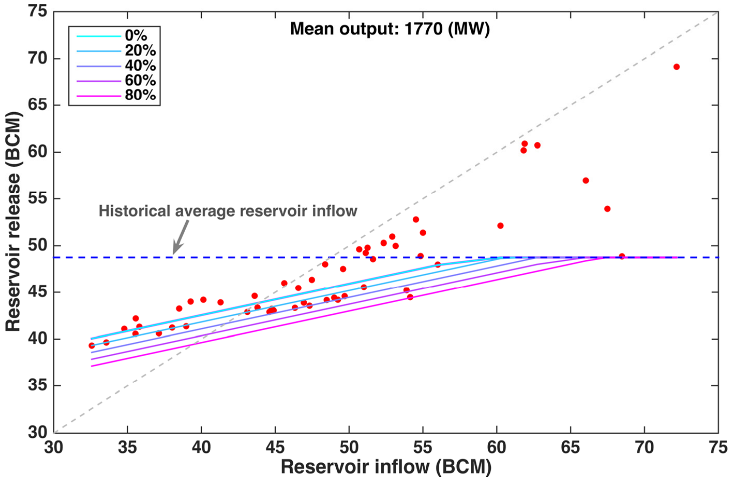
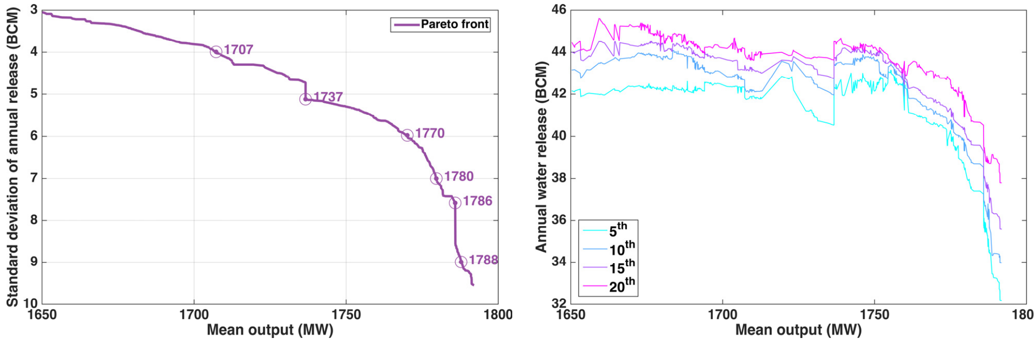


Fig. 4 Sample drought mitigation policy with varying exceedance levels (z=0%, 20%, 40%, 60%, and 80%)

4. Results and Discussion

4.1. Multi-objective reservoir operation with no drought policy

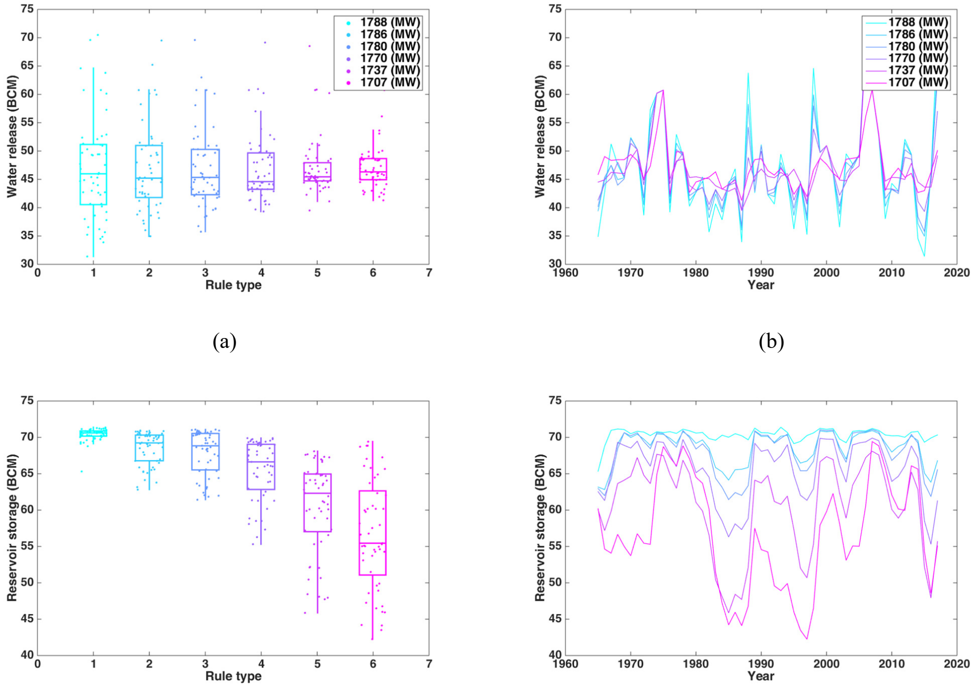
Multi-objective optimization of GERD reservoir operating rules illustrates that there is a trade-off between reservoir power generation and deviation in reservoir annual water releases (Fig. 5 (a)). More specifically, GERD monthly mean power generation output is estimated at 1788, 1708, 1737, and 1707 MW for annual release standard deviations of 9, 7, 6, 5, and 4 BCM, respectively. Although the reservoir operating rules are not optimized for maximum annual water release, less $Std\left(Q_y^{out}\right)$ typically leads to relatively more releases in dry conditions (e.g., 5th, 10th, 15th, and 20th percentiles), especially when the mean output is greater than 1750 MW (Fig. 5 (b)). 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.



(a) (b)

Fig. 5 Multi-objective optimization results of reservoir operating rules in terms of (a) Pareto front and (b) the relationship between power generation and 5th, 10th, 15th, and 20th percentile of annual water release.

The reservoir operating rules simulation results under various mean output levels illustrates that the variance of annual water release shrinks and reservoir storage declines as power output decreases (Fig. 6). Although the median values of annual water release for all six output levels are approximately the same (around 45 BCM), the reservoir operating rules with more output generally have lower minimum water releases (Fig. 6 (a) and (b)), especially in dry periods. In general, greater reservoir storage leads to more power generation (see equation (1)) and vice versa, thus the reservoir operating rules generating 1788 MW of mean output produces the highest water level, and 1707 MW the lowest (Fig. 6 (d)). Also, there is a clear trade-off between the variance of reservoir storage and water release (Fig. 6 (a) and (c)); smaller reservoir storage variance ensures higher reservoir levels, greater water release variance, and lower minimum water releases. It is worth noting that the 75th and 90th percentiles of reservoir storage are much more sensitive to power output than those of water release. More specifically, the 90th percentile of water release for rule types 5 and 6 are almost the same, however, the corresponding percentile of reservoir storage (as well as power output) are notably different (Fig. 6 (a) and (c)). This indicates that rule type 6 may be inferior to rule type 5 despite of the trade-off in Fig. 5 (a). Thus, it is necessary to analyze the operation results (including water release and power generation) before selecting the reservoir operating rules based on the Pareto front in Fig. 5 (a).



(a) (b)

(c) (d)

Fig. 6 Boxplots and values of annual reservoir (a)(b) water release and (c)(d) storage for various reservoir operating rules.

Comparing across rule types, rules with high mean output generate more hydropower mainly in wet years (Fig. 7). In particular, rule type 1 (1788 MW) can generate approximately 670, 760, and 670 MW more than rule 6 (1707 MW) in years 1988, 1998, and 2017, respectively. In these years, the annual reservoir inflow is greater than 65 BCM (Fig. 7). It is worth noting that the annual reservoir inflow in the previous one or two years (i.e., year 1987, 1997, and 2015) is less than 38 BCM (Fig. 7) and the corresponding reservoir storage is much higher than in rule types (Fig. 6 (d)). Thus, it can be inferred that rule types with larger power generation can increase the mean output by releasing less water during dry years to maintain relatively higher reservoir water levels. In this way, more water will be available and higher head (H_t^p in equation (1)) can be achieved for future wet years, leading to much more power generation.

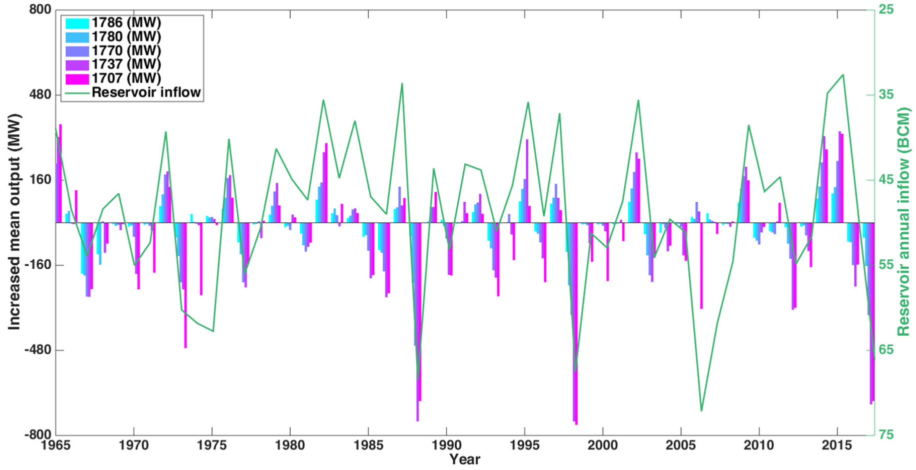


Fig. 7 Net power generation output of various reservoir operating rules compared with rules producing a mean output of 1788 MW.

However, releasing less water in dry years is not a strategy preferred by downstream countries, which could further 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. 8). In comparison, rule type 3 (1780 MW) releases more water than reservoir inflow in dry years. As power generation decreases further the number of years with reservoir water releases exceeding inflow increases. Applying a linear regression between annual reservoir inflow and water release (see the lines in Fig. 8), a drought mitigation policy (equation (10)) can be extracted to constraint annual water release in reservoir operation. Rule types favoring more power generation generally produce a steeper gradient in the drought mitigation policy.

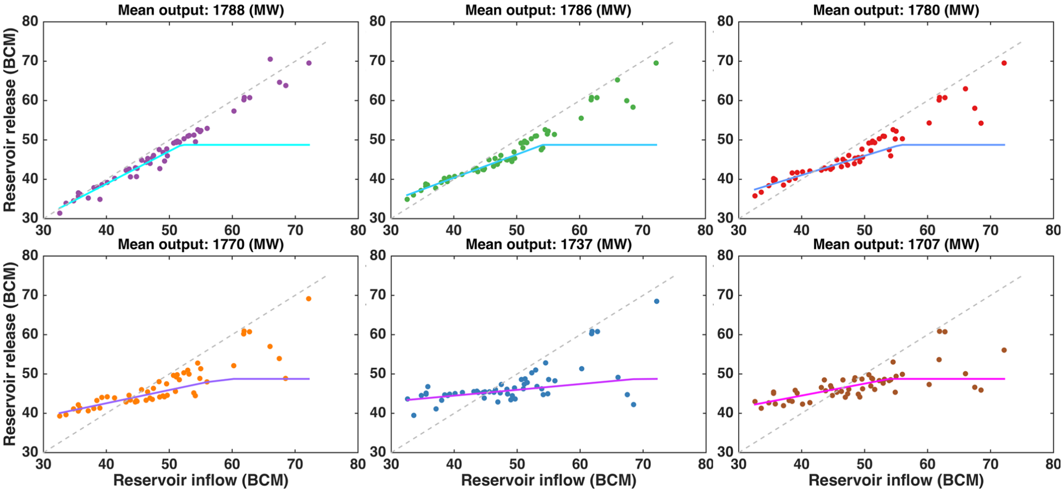
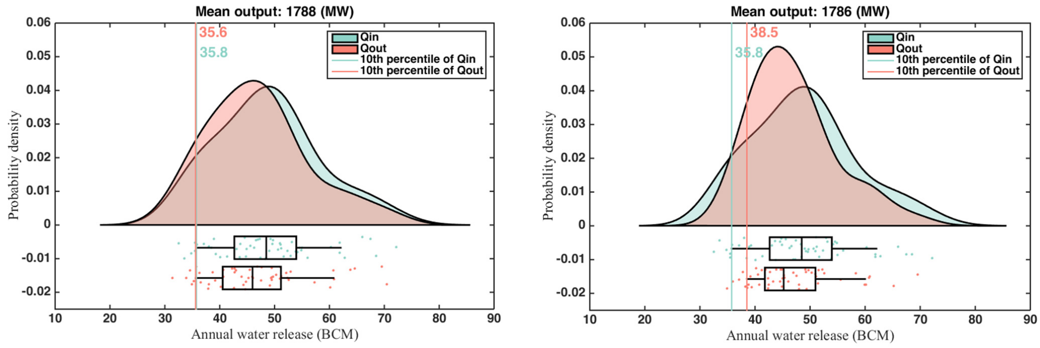


Fig. 8 Relationship between annual reservoir inflow and water release (points) and the corresponding drought mitigation policy (lines) for various power generation levels.

4.2. **Drought policy selection and analysis**

To select the most suitable drought mitigation policy, both the corresponding power generation and distribution of annual reservoir water releases need to be evaluated. In general, the distributions of annual reservoir inflow and releases are significantly different when the reservoir operation is 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). In contrast, the 10th percentile of annual reservoir inflow is constant at 35.8 BCM. Thus, except for rule type 1 with equal inflow and outflow volumes, all other rule types ensure that the 10th percentile of releases is greater than inflows. This equates to supplementing downstream flows to address drought conditions when the 10% exceedance value of annual reservoir inflow is used as the drought threshold. Further, even when reservoir inflow is less than its 20th percentile value, water releases are greater than annual reservoir inflow except for rule type 1 (Fig. 10). However, when the threshold exceeds the 25th percentile, only solutions based on rule type 3-6 contain annual releases surpassing inflow. These distributions (Fig. 9 and Fig. 10) can provide critical insights during riparian negotiations regarding trade-offs between power generation and supplementing downstream flows during drought conditions. Although only six candidate solutions are illustrated here, more representative solutions may be analyzed in practice.



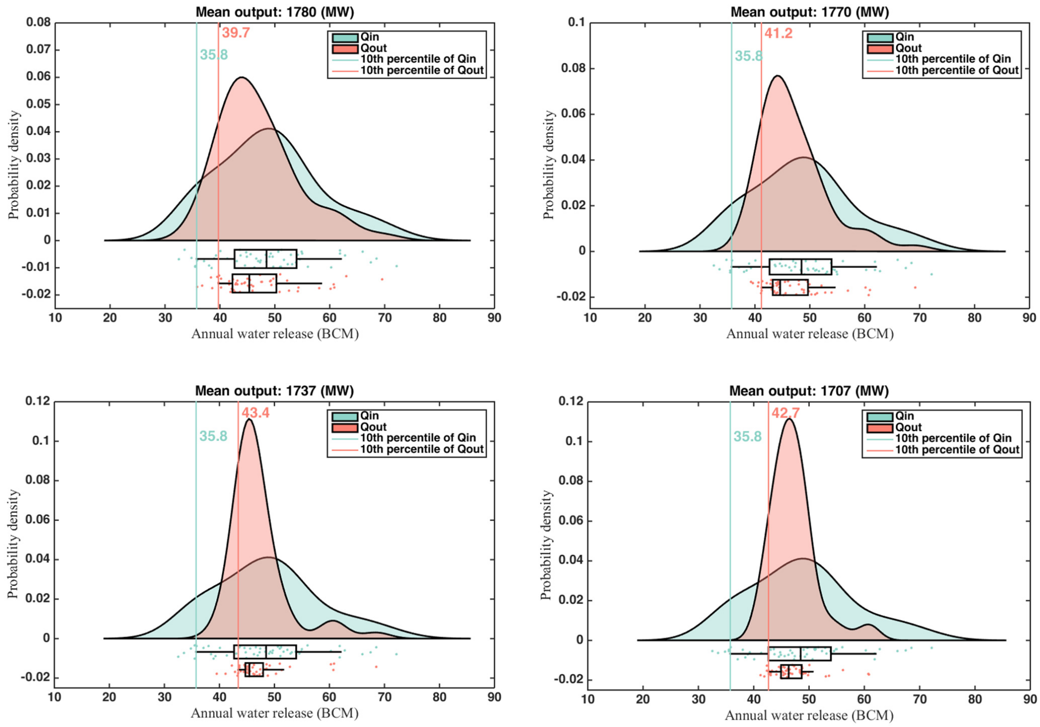


Fig. 9 Kernel distribution of annual reservoir inflow (Qin) and water release (Qout) under different power generation levels (1965-2017). Vertical lines represent the 10% exceedance value.

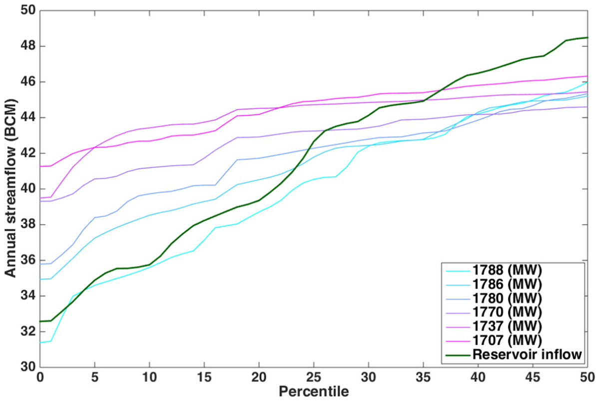


Fig. 10 Percentiles of annual reservoir inflow and water release under various power generation levels.

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Incorporating these drought policies (Fig. 8), reservoir operating rules are optimized again for maximum power generation and minimum deviation of annual release volumes, illustrating varying trade-offs for drought policies 1-6 (Fig. 11). Drought policies produce similar but not exact hydropower generation as the original operating rules (e.g. policy 1 original = 1788MW, drought = 1791MW); the standard deviation of annual releases also does not change significantly. Comparing drought policies producing a high level of hydropower production (e.g. moving from policy 1 to 2), a small trade-off in production (~4MW) leads to approximately a 2 BCM decrease in the standard deviation of annual releases. For lesser hydropower production policies (e.g. moving from policy 5 to 6), a larger difference of 37MW leads to a smaller (~1 BCM) change in the standard deviation of annual releases.

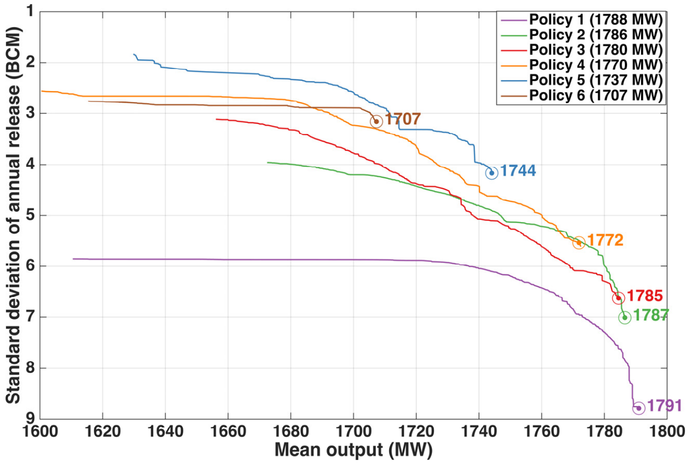


Fig. 11 Multi-objective optimization of reservoir operating rules with drought mitigation policies.

To further evaluate the effectiveness of these drought policies, the mean power output, 10th percentile of annual water releases, and standard deviation of annual water releases obtained from each policy (corresponding to the Pareto fronts in Fig. 11) are analyzed (Fig. 12). In Fig. 12, each line presents a set of reservoir operation results corresponding to a solution from each of the six Pareto fronts in Fig. 11, based on an expectation of (long-term) monthly average inflow conditions (i.e. not perfect information.)

Predominantly, rules including the drought mitigation policy have higher 10th percentile of annual water release values than original rules. For policies 1 and 2, in addition to notably more 10th percentile annual release values, mean power output does not appreciably drop, thus simultaneously supplementing downstream flows during drought without significant power output losses. Although policies 3-6 provide more 10th percentile of annual releases than the original rules, power output drops; however the standard deviation of annual water releases is significantly less, which indicates that all policies (derived from all power generation levels) can effectively address downstream drought.

Since these drought policies are effective even using climatological forecast information, it can be inferred that the effectiveness of drought mitigation policies for the GERD case does not rely on accurate forecast information. This bodes well for other cases lacking accurate hydrological forecasts.

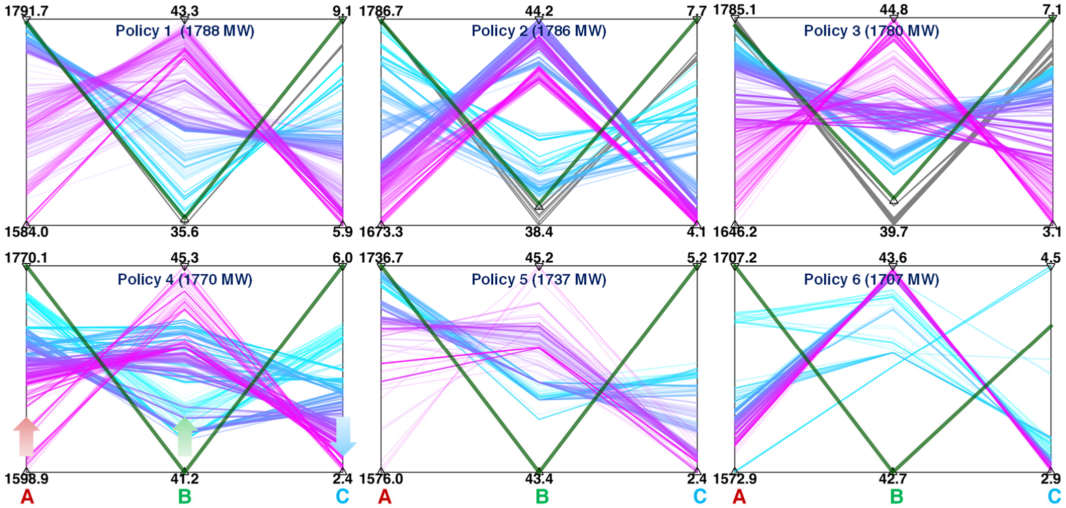


Fig. 12 Parallel plots of multiple objectives (A: mean output (MW), B: 10th percentile of annual water release (BCM), C: standard deviation of annual water release (BCM)). The bold green line refers to the reservoir operation without the drought policy.

After re-optimization with the drought policy information included, greater power generation and smaller values of the standard deviation of annual water releases are produced. More importantly, the re-optimized rules can fully ensure minimum annual releases under different reservoir inflow levels (Fig. 13).

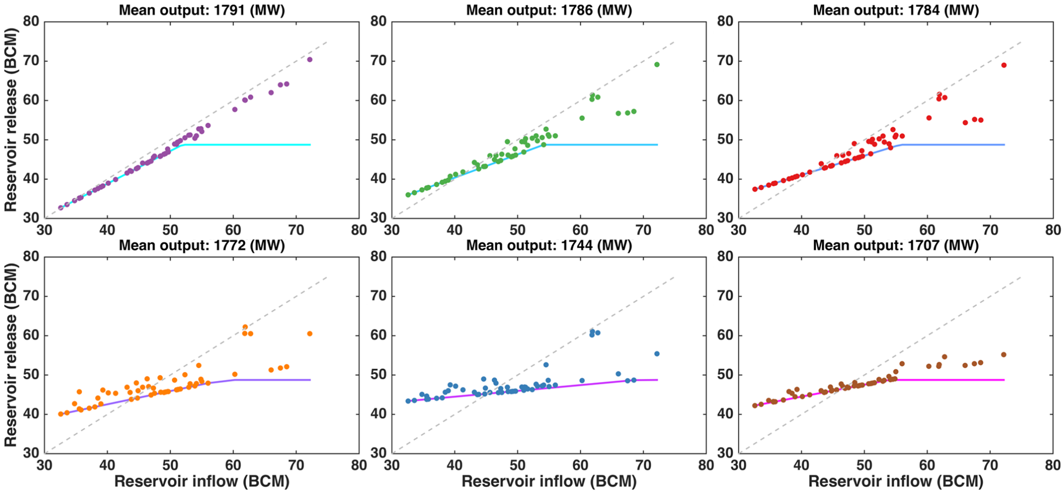
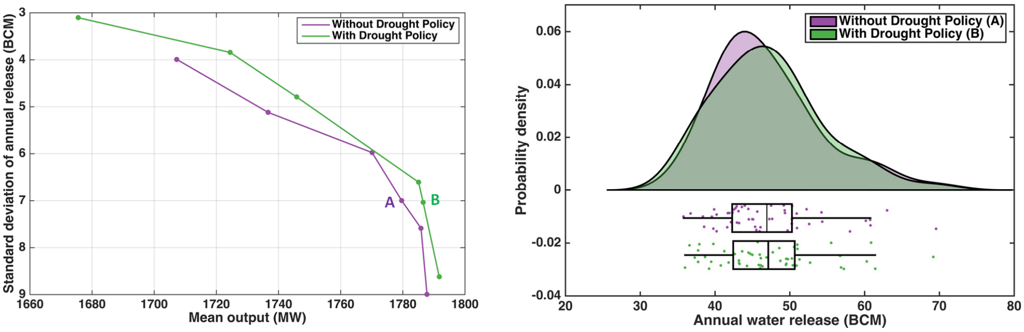


Fig. 13 Relationship between annual reservoir inflow and releases using re-optimized reservoir operating rules; drought policies represented by lines.

These rules produce slightly more power than the original rules for equivalent standard deviation of annual release values (Fig. 14(a)) even though they are re-optimized constrained on annual water releases for drought conditions). Performance of the re-optimized rules, however, mainly depends on the exceedance parameter z in equation (10); more conservative drought mitigation policies (with larger z values) can generate more power. Because the trade-off between power generation and the standard deviation of annual releases is similar between the original rules and drought policy rules (Fig. 14(b)), it is feasible to base negotiations on the original rules in this case, as the expected drought policy outcomes are superior.



(a) (b)

Fig. 14 (a) Pareto fronts of reservoir operation with and without drought policy; (b) boxplot of reservoir storage for solution A and B in the Pareto fronts and kernel distribution of annual reservoir water releases with and without the drought policies.

5. Conclusions

Reservoir operations in transboundary river basins are often complex given diverse and potentially conflicting objectives between upstream and downstream countries. Applying the water-sharing policy framework proposed here for the Grand Ethiopian Renaissance Dam on the Blue Nile River, we establish a relationship between downstream and upstream water availability, derive water-sharing policies from multi-objective optimization results of reservoir operating rules, and analyze the effectiveness of these policies during drought periods. We demonstrate that a framework incorporating RBF-based rules and a drought-focused water sharing policy can lead to robust reservoir decision-making. There is a clear trade-off between power generation and the standard deviation of reservoir releases; however, effective policies are available to balance this trade-off, even considering drought periods.

This framework here is based on annual flows, however seasonal and monthly scale operations could be of primary importance in smaller basins or for smaller-capacity reservoirs. Also, many other objectives and constraints including firm power output, agricultural water supply reliability, and ecosystem functions could be considered. Future research could explore drought-focused water sharing policies guiding reservoir operations across multiple time scales simultaneously and the application of seasonal-to-sub-seasonal inflow forecasts.

Code and Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution

Guang Yang developed the model code and performed the simulations, visualizations, and original draft preparation. Paul Block conceptualized the idea and performed data curation and writing- reviewing and editing.

Competing interests

The authors declare that they have no conflicts of interest in this work.

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