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. 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. 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

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17 effectiveness of the drought-specific water sharing policies. With a case study of the Grand Ethiopian

18 Renaissance Dam (GERD) on the Blue Nile River, it is demonstrated that the derived water sharing policy

19 can balance GERD power generation and downstream releases, especially in dry conditions, effectively

20 sharing the hydrologic risk in inflow variability among riparian countries. The proposed framework offers

21 a robust approach to inform water sharing policies for sustainable management of water resources.

22 **Keywords:** Reservoir operation; Water sharing policy; Drought mitigation; Multi-objective optimization;

23 Grand Ethiopian Renaissance Dam.

1. Introduction

25   Rapid population growth and socio-economic development exacerbate stress on the management of

26 water resources globally (Vörösmarty et al., 2000;WWAP, 2019). Surface-water reservoirs and their

27 effective management is one of the most efficient means to reduce this stress by reallocating water

28 resources spatially and temporally (Gaudard et al., 2014). Thus in recent decades, many models and

29 strategies have been investigated to inform and improve reservoir operation decision-making (Chaves and

30 Chang, 2008;Cancelliere et al., 2002;Herman and Giuliani, 2018;Karamouz and Houck, 1982;Giuliani et

31 al., 2014;Oliveira and Loucks, 1997). For example, Karamouz and Houck (1982) optimize monthly

32 reservoir releases by deterministic dynamic programming and build a linear reservoir operation model

33 conditioned on the relationship between optimal releases and reservoir state variables. Cancelliere et al.

34 (2002) built a non-linear reservoir operation model by using neural network techniques to improve

35 reservoir irrigation water supply during drought conditions. Herman and Giuliani (2018) design a tree-

36 based policy which is flexible and interpretable for reservoir operation over multiple timescales. In general,

37 reservoir decisions (e.g., water releases and power generation) are determined using reservoir operating

38 rules with available input variables including reservoir state (e.g., reservoir water level) and hydrological

39 conditions (e.g., reservoir inflow) (Oliveira and Loucks, 1997).

40   Reservoir operating rules are typically derived using fitting-based and simulation-optimization-based

41 approaches. In fitting-based rules derivation (policy fitting), reservoir operation decisions are optimized

42 and subsequently fitted with input variables using linear regression (Bhaskar and Whitlatch Jr, 1980),

43 artificial neural networks (Cancelliere et al., 2002), fuzzy inference (Chang and Chang, 2001), and

44 decision trees (Wei and Hsu, 2008). In simulation-optimization methods, the parameters of reservoir

45 operating rules are optimized with an iterative simulation-based search algorithm in which the

46 performance is evaluated directly from reservoir operation simulations (Le Ngo et al., 2007;Rani and

47 Moreira, 2010). For example, Giuliani et al. (2015a) approximated reservoir operating rules by using

48 artificial neural networks and radial basis functions (RBFs) and optimized the rules for multi-purpose

49 water reservoirs with an evolutionary algorithm. A policy fitting approach requires an optimal set of

50 reservoir inflows, storages, and releases and its effectiveness highly depends on the performance of the

51 optimized reservoir operation model; however, the rules derivation is interpretable and intuitive when

52 optimal reservoir decision-making is highly correlated with state variables. In contrast, simulation-

53 optimization-based approaches do not rely on existing optimal reservoir operations and thus it is generally

54 more flexible than fitting-based rules.

55   Most of these approaches are implemented in water resources systems contained within a basin or

56 jurisdiction in which the benefits (e.g. power generation, water supply, and ecosystem function

57 maintenance) can be quantified and evaluated (Reddy and Nagesh Kumar, 2007;Feng et al., 2018;Yang

58 et al., 2016). Reservoir operations are necessarily more complex after considering a wide variety of social,

59 political, economic, and cultural conditions in river basins (Zeitoun and Mirumachi, 2008). Disputes and

60   conflicts are not uncommon between riparian states in river basins when water sharing agreements are

61   non-existent or non-enforceable and claims may be defined based on historical use. For example, the Nile

62   River serves eleven countries, 250 million people (Nile Basin Initiative, 2017), and is vital to agriculture,

63   industry, and hydropower, (Paisley and Henshaw, 2013), yet no mutually agreed upon water sharing

64   policies exist. (The 1959 agreement (Guariso and Whittington, 1987) has been repudiated by upstream

65   riparian states.) Acknowledging significantly divergent interests and a history of conflict and distrust,

66   quantifying the impact of reservoir operation on downstream benefits is challenging, hindering

67   development of water sharing strategies (Link et al., 2016).

68   According to the Transboundary Freshwater Dispute Database (McCracken and Wolf, 2019), the

69   existing 310 international river basins across the world are shared by 150 countries and disputed areas,

70   cover 45% of the Earth's land surface, and contribute to 60% of the world's freshwater resources. As

71   suggested by Sadoff and Grey (2002), it is critical to understand and account for the range of inter-related

72   benefits resulting from the development of international rivers in a cooperative way. Such cooperation of

73   water resources development in international river basins has been widely investigated in recent years (Li

74   et al., 2019;Luchner et al., 2019;Arjoon et al., 2016;Wheeler et al., 2018;Degefu et al., 2016). For example,

75   Arjoon et al. (2016) proposed a benefit-sharing method based on the optimization results from a hydro-

76   economic model and evaluated the value of cooperative water management in the Eastern Nile River basin;

77   Li et al. (2019) analyzed the water benefits of stakeholders from cooperation under different reservoir

78   operation scenarios by using cooperative game theory methods; Luchner et al. (2019) simulated reservoir

79   operations and water allocation in an international river basin in Central Asia and found that international

80   cooperation in the power sector can ease the conflict between upstream hydropower production and

81   downstream irrigated agriculture.

82   Most previous studies focus on illustrating the importance of a cooperative strategy through water

83   system optimization and simulation (Dombrowsky, 2009;Tilmant and Kinzelbach, 2012) and evaluating

84   the benefits of cooperative operation (Goor et al., 2010;Anghileri et al., 2013;Uitto and Duda,

85   2002;Luchner et al., 2019). There is less literature (Wheeler et al., 2016;Li et al., 2019;Degefu et al.,

86   2016;Teasley and McKinney, 2011), however, addressing strategies for reaching an agreement or

87   consensus on water resources development amongst downstream and upstream riparian countries. Also,

88   although cooperation can result in a win-win situation for both downstream and upstream stakeholders,

89   cooperative water use strategies are obstructed by single-sector interests, especially when long-term

90   commitments are involved (Wu and Whittington, 2006). More specifically, it is often difficult to achieve

91   a mutually agreed-on cooperation strategy given divergent solution preferences by stakeholders.

92   Additionally, benefit sharing policies rely heavily on hydro-economic modeling and cost-benefit

93   analysis (Jeuland et al., 2014), which strives to maximize overall aggregated benefits and subsequently

94   allocate benefits in an equitable way. However, (1) the aggregation of benefits can hide important trade-

95   offs and may increase the risk of floods and droughts for maximum economic benefit; (2) there is no

96   standard that regulates how benefits of water use from various sectors (e.g., drinking, agriculture, industry,

97   recreation, and navigation) are quantified and what mechanism should be applied to equitably

98   allocate/share the benefits (Acharya et al., 2020); and (3) there is presently no basin-wide authority to

99   enforce benefit allocations (e.g. payments from one country to another) although institutions such as the

100   Nile Basin Initiative could serve in this role (Arjoon et al., 2016). Thus, water sharing policies considering

101   the trade-off between economic benefits and drought risk, rather than benefit sharing policies based on

102   cooperative operation strategies analysis, are investigated in this study. The policies will be flexible,

103   interpretable, and more importantly drought-focused such that downstream drought mitigation will

104   become an inherent part of the water sharing framework.

105   In this study, a systemic framework is proposed to derive operational reservoir water-sharing policies

106   using multi-objective optimization for water use conflict mitigation. Specifically, (1) optimize reservoir

107   operating rules and establish trade-off between upstream benefits and downstream drought risks, (2)

108   simulate reservoir operation with the candidate (optimal) rules, evaluate performance, and select the most

109   suitable rules for balancing benefits, (3) derive water-sharing policies conditioned on reservoir operations

110   and water availability, and (4) re-optimize reservoir operating rules incorporating derived water-sharing

111   policies to evaluate effectiveness and performance. The drought-focused water-sharing policies are

112   interpretable as they are derived from and evaluated on reservoir operation simulations from existing

113   optimal rules. Further, the policies are considered flexible by offering opportunities for informing

114   upstream-downstream negotiations. The Grand Ethiopian Renaissance Dam (GERD) in Ethiopia is

115   selected to demonstrate the framework and illustrate how operational water-sharing strategies, reflective

116   of upstream and downstream demands and natural hydrologic variability, can promote water-sharing

117   agreements between upstream and downstream countries.

118 2. Study Area and Data

119 2.1. **The Blue Nile Basin and the Grand Ethiopian Renaissance Dam**

120   The Blue Nile River, the largest tributary of the Nile River, originates at Tana Lake in Ethiopia and

121   merges with the White Nile River in Khartoum, Sudan. Average annual rainfall in the upper part of the

122   basin varies between 1200 and 1800 mm (Conway, 2000), with a dominant rainy season in June–

123   September contributing approximately 70% of mean annual precipitation. During this season, the Blue

124   Nile contributes nearly 80% of the total Nile River streamflow (Swain, 2011) and the average annual

125   runoff of the Blue Nile at Roseries, near the Ethiopia–Sudan border, is approximately 49 km^3 (Wheeler et

126   al., 2016), thus it plays a significant role in livelihood and development in Ethiopia, Sudan and Egypt.

127   Ethiopia started constructing the Grand Ethiopian Renaissance Dam (GERD) across the Blue Nile

128   River in 2011, approximately 15 km upstream of the Sudanese border (Fig. 1). When completed, the

129   GERD will become the largest hydroelectric dam (installed capacity more than 5,000 MW) in Africa

130   (Government of Ethiopia, 2020) and will have a total reservoir capacity of 74 billion cubic meters. The

131   GERD is expected to produce an average of 15,130 GWh of electricity annually (with mean output of

132   1727 MW) (Tan et al., 2017;Tesfa, 2013), which will contribute to Ethiopia's national energy grid and

133   feed the East African power pool (Nile Basin Initiative, 2012). There is uncertainty in media reports

134   regarding the total installed capacity for GERD which ranges from 5,150 MW (Ezega News, 2019b) to

135   6,000 MW (Ezega News, 2019a;Zelalem, 2020). A value of 6,000 MW, which was applied both in the

136   annual electricity production estimation and previous publicly available scientific studies (Tesfa,

137   2013;Yang et al., 2021), is opted for this study. It is worth noting that re-running the simulations with an

138   installed capacity of 5,150 MW instead of 6,000 MW does not change principal conclusions. Although the

139   GERD is primarily designed for hydropower, and thus non-consumptive, operating to maximize power

140   generation may result in a water release schedule significantly different from the natural annual cycle,

141   particularly considering drought periods, with implications to Sudan and Egypt. This is the crux of the

142   current hydro-political confronting the riparian countries.

143   In this study, GERD reservoir operation rules are developed considering power generation and

144   downstream water release (including turbine outflows and spillage losses) simultaneously to mitigate

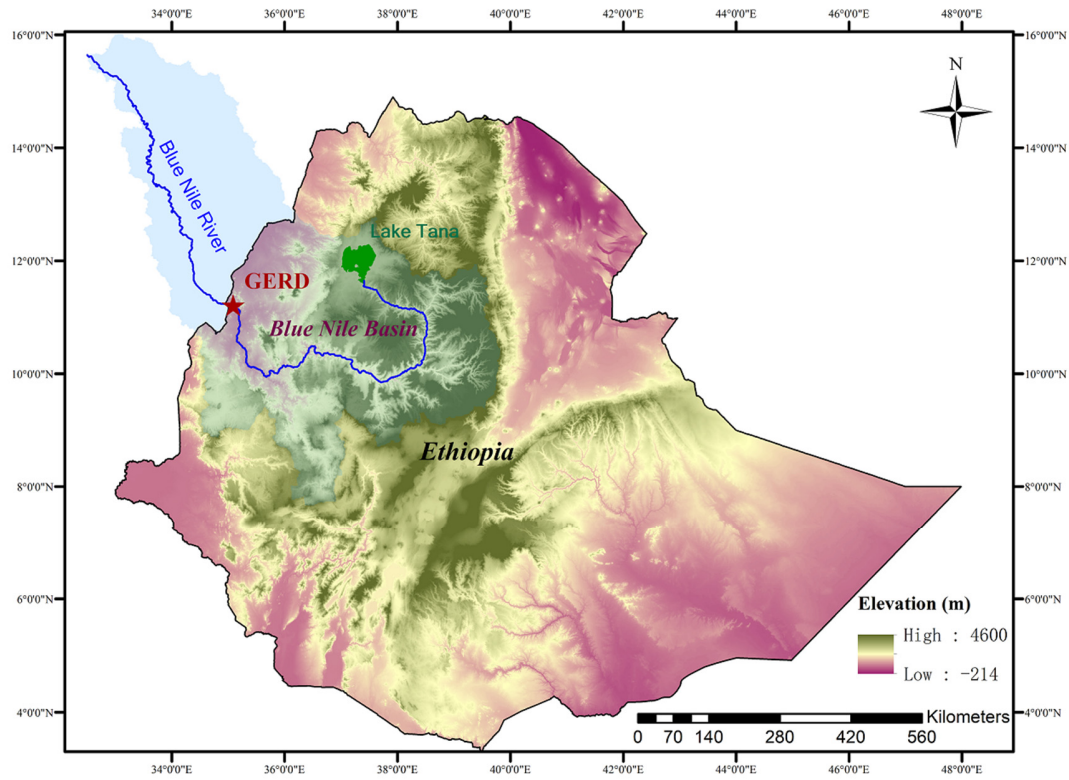
145   upstream-downstream water use conflicts, particularly tailored to drought periods. The study investigates

146   water-sharing (drought mitigation) policy derivation procedures (reservoir operation simulation and

147   optimization, power generation and downstream water release analysis, drought mitigation policy

148   extraction and validation) balancing GERD production and downstream flow volumes. Historical monthly

149 inflow at El Diem gauging station (located just downstream of the GERD site) for 1965-2017 (Fig. 2) are

150 applied.

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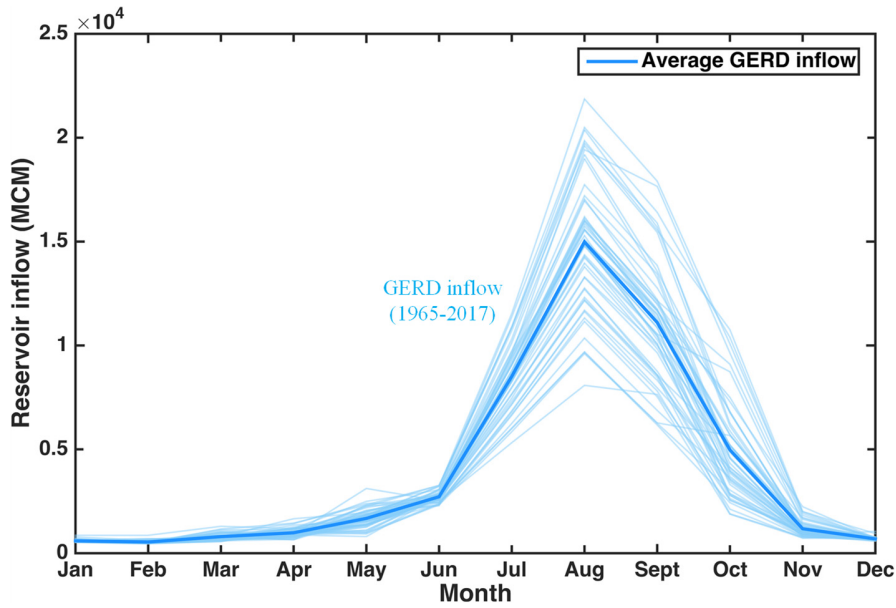
152 Fig. 1 Blue Nile basin with Ethiopia country borders and the location of the GERD reservoir

153

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

3. Models and Methods

156   The procedure for water sharing policy derivation and evaluation including large-scale reservoir

157   operations is introduced in this section (Fig. 3). In summary, the process is as follows:

158   • First: optimize the reservoir operating rules approximated with Radial Basis Functions (RBFs)

159   and obtain the Pareto front for upstream and downstream benefits trade-off.

160   • Second: select feasible solutions on the Pareto front according to the requirements of power

161   generation and drought mitigation; specifically, for a given power generation level, the

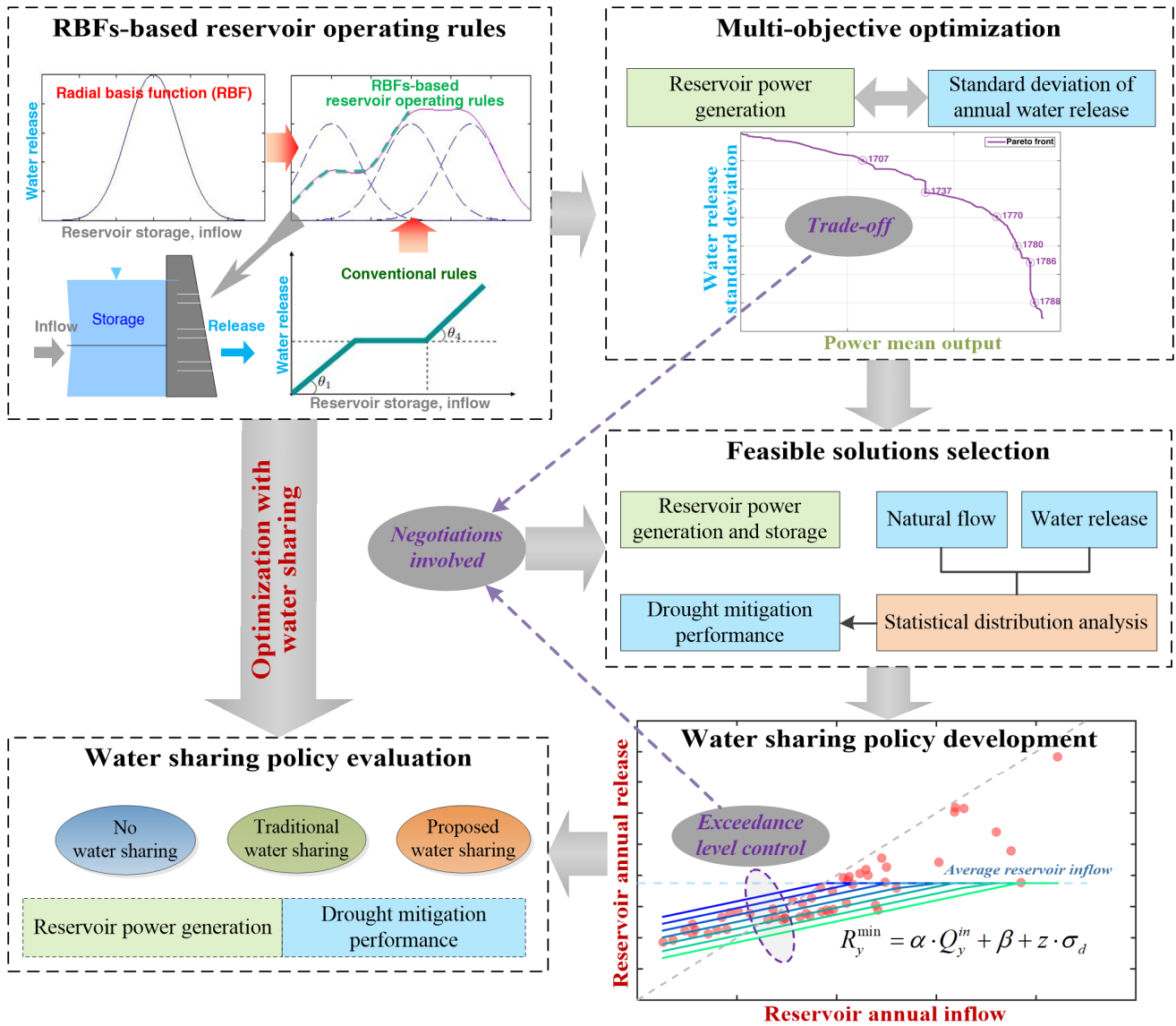
162   distribution of annual water release is analyzed with special attention to low flow years.

163   • Third: define the relationship between annual reservoir inflow and releases based on the selected

164   feasible solutions; the policy can be further framed as a function of reservoir annual inflow

165   predictions.

166   • Fourth: incorporate the policy into general RBFs-based rules to evaluate policy effectiveness and

167   robustness.

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

170 3.1. **Reservoir operation model**

171   The primary purpose of the GERD reservoir is hydropower production; this objective function can

172 be described as follows:

173
$$Max \quad E = \sum_{t=1}^{T} P_t \cdot \Delta t, \quad P_t = \eta \cdot g \cdot \rho \cdot Q_t^P \cdot H_t^P / 1000 \tag{1}$$

174 where E is hydroelectricity generation (kW h) during total number of operational periods T; P_t is the

175 power generation output (kW) during time period t and Δt is the time (h) of a single period; η, g, and ρ

176 refer to the dimensionless hydropower generation efficiency of the turbines (set as 0.9 in this study),

177 gravitational acceleration (9.8 m/s^2), and water density (1000 kg/m^3), respectively; and Q_t^P and H_t^P are

178 reservoir release for power generation (m^3/s) and average power head (m) in period t, respectively.

179 In lieu of modeling specific water requirements downstream of the GERD, minimizing annual water

180 release variance is applied. This approach favors reliable releases yet also reflects natural hydrologic

181 variability, and can be described as below.

182
$$Min \quad Std\left(Q_y^{out}\right) = \sqrt{\frac{\sum_{y=1}^{Y}\left(Q_y^{out} - \bar{Q}_y^{out}\right)^2}{Y}} \tag{2}$$

183 where Q_y^{out} is the reservoir water release (which includes turbine outflows and spillage losses) in year y

184 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

185 all operational years Y, respectively.

186 Physical and operational reservoir constraints are listed as below.

187 (a) Water balance:

188
$$S_{t+1} = S_t + \left(Q_t^{in} - Q_t^{out}\right) \cdot \Delta t - EP_t \tag{3}$$

189   where S_t and S_{t+1} are reservoir storage (m³) in period t and $t+1$, respectively, Q_t^{in} represents reservoir

190   inflow (m³/s) in period t, Q_t^{out} is reservoir release (m³/s) in period t, and EP_t is the sum of evaporation and

191   seepage from the reservoir (m³) in period t.

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

193   The reservoir structural and operational constraints can be expressed as:

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

195   where $S^{\min}$ and $S^{\max}$ are the minimum (14.8 billion m³) and maximum (74 billion m³) allowable reservoir

196   storage.

197   Additionally, S^{begin} and S^{end} represent the initial and final reservoir storage (m³) for simulations

198   (both of them are set as 65.1 billion m³), respectively, and are prescribed as:

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

200   (c) Reservoir release limits:

201   The reservoir release constraints are expressed as:

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

203   where QL_t and QU_t are the minimum and maximum release (m³/s) in period t, respectively. The

204   expected guidelines for GERD reservoir water release are not explicitly available, thus releases are set

205 higher than zero and lower than the maximum reservoir inflow (21.9 billion m³/month) during the high-

206 flow season to reduce or eliminate downstream floods.

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

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

209 where PL_t and PU_t are the minimum (0 MW) and maximum (6000 MW) power limits in period t,

210 respectively.

211 3.2. **Reservoir operating rules**

212 In this study, reservoir water releases are conditioned on radial basis functions (RBFs), a non-linear

213 function approximating method (Buşoniu et al., 2011) which can provide universal approximation (Tikk

214 et al., 2003) and ensure a flexible reservoir operating rules structure. For more applications of RBF models

215 in reservoir operation see Giuliani et al. (2015a). The reservoir operating rules are defined as below.

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

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

218 where U is the number of RBFs, $\varphi(\cdot)$ and ω_u are the weights of the uth RBF, M is the number of input

219 variables X_t, and $\mathbf{c}_u$ and b_u are the M-dimensional center and radius vectors of the uth RBF, respectively.

220   Because water release generally depends on the reservoir state (Revelle et al., 1969) and inflow, with

221   intra- and inter-annual variability, reservoir storage S_t, inflow Q_t^{in}, and seasonal information τ_t (where τ_t

222   refers to the position of the current period (month) t within a water year) are selected as input variables

223   and $X_t = \left(S_t, Q_t^{in}, \tau_t \right)$.

224   In this study, the number of RBFs is set to four (as in Giuliani et al. (2015b)), thus U=4 and M=3 (three

225   input variables) in equation (8)-(9) resulting in 20 parameters in the RBFs-based rules. The parameters in

226   RBFs-based rules are optimized with a simulation-optimization model (Rani and Moreira, 2010), using

227   the Pareto-Archived Dynamically Dimensioned Search (PA-DDS) evolutionary algorithm which has been

228   successfully applied to reservoir operating rules optimization (Yang et al., 2020). The procedure of the

229   PA-DDS algorithm has been described in detail by Asadzadeh and Tolson (2013).

230   3.3. **Drought-focused water sharing policy**

231   To ensure downstream water supply, the GERD reservoir will need to be operated under minimum annual

232   water release constraints. Apart from the RBFs-based rules determining the reservoir water release in each

233   time step (months), a drought mitigation policy is also adopted to address dry periods. The policy is based

234   on annual time steps and represented as a linear regression between annual reservoir inflow and water

235   release. More specifically, the minimum annual reservoir water release can be determined by the following

236   equation:

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

238   where Q_y^{in} and $R_y^{\min}$ refer to reservoir inflow and minimum reservoir water release during year y,

239   respectively; α and β are regression parameters estimated from simulations containing reservoir

240   inflow values below the historical average (approximately 49 BCM). An exceedance parameter z is

241   multiplied by the standard deviation of the regression residuals σ_d to vary how conservative the drought

242   mitigation policy is (see Fig. 4 for a visualization of exceedance parameters). This policy design favors

243   downstream releases under drought conditions by supplementing what would occur under natural flow

244   conditions, however as a trade-off, the minimum reservoir release in any year will not exceed the historical

245   average reservoir inflow (see the horizontal line in Fig. 4).

246   The drought policy is conditioned on reservoir inflows and releases for a transparent, interpretable, and

247   intuitive process, which is important especially when negotiations are involved. The gradient of the policy

248   line is highly correlated with variability in reservoir releases, in general, as the slope increases, so does

249   the variability in releases. Thus, the parameter α can be estimated from the trade-off between reservoir

250   power generation and downstream water release variability. The exceedance parameter z further controls

251   the degree of drought mitigation; larger z values indicate higher drought thresholds (see the intersection

252   between the policy line and 1:1 dash line in Fig. 4). In the drought policy design, these two parameters can

253   be estimated separately to isolate their impact on drought mitigation performance. This case study mainly

254   focuses on the impact of the first parameter as the exceedance parameter z is eventually set as 0%.

255   In this study, the drought mitigation policy is designed with annual streamflow data, however reservoir

256   operating rules are derived for monthly operation. With reservoir storage in current month S_m, reservoir

257   inflow in current month Q_m^{in}, and the predicted reservoir inflow during the rest of the year $Q_{m+1}^{\prime in}$, …, $Q_{12}^{\prime in}$,

258   the reservoir water release in current month Q_m^{out} and the rest of year $Q_{m+1}^{\prime out}$, …, $Q_{12}^{\prime out}$ can be obtained from

259   equations (8) and (9), thus the annual reservoir inflow and water release can be estimated as below.

260

$$Q_y^{\prime in} = \sum_{1}^{m} Q_m^{in} + \sum_{m+1}^{12} Q_m^{\prime in} \qquad\qquad (11)$$

$$261 \qquad\qquad Q_y'^{out} = \sum_1^m Q_m^{out} + \sum_{m+1}^{12} Q_m'^{out} \qquad\qquad (12)$$

262   The minimum reservoir water release in year y can be estimated from equation (10) as $R_y'^{\min}$. To ensure

263   the minimum annual water release obligation is met, if the estimated annual reservoir water release $Q_y'^{out}$

264   is lower than $R_y'^{\min}$, the release in current month Q_m^{out} will be corrected according to the following:

$$265 \qquad\qquad Q_m^{out} = Q_m^{out} + \left(R_y'^{\min} - Q_y'^{out} \right) \times \frac{Q_m^{in}}{\sum_m^{12} Q_m'^{in}} \qquad\qquad (13)$$

266   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

267   year, the annual reservoir inflow estimation $Q_y'^{in}$ will be equal to actual annual inflow $\sum_1^{12} Q_m^{in}$ and the

268   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

269   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

270   reservoir release Q_y^{out} will always be greater than or equal to the specified minimum reservoir water release

271     $R_y^{\min}$ and it can be inferred that the minimum annual release $R_y^{\min}$ is mainly determined by the policy

272   parameters α, β, and z, rather than forecast accuracy.

273   As illustrated in equation (10) and Fig. 4, the minimum annual reservoir release can be estimated from the

274   annual reservoir inflow after the drought policy line is determined. Considering actual annual reservoir

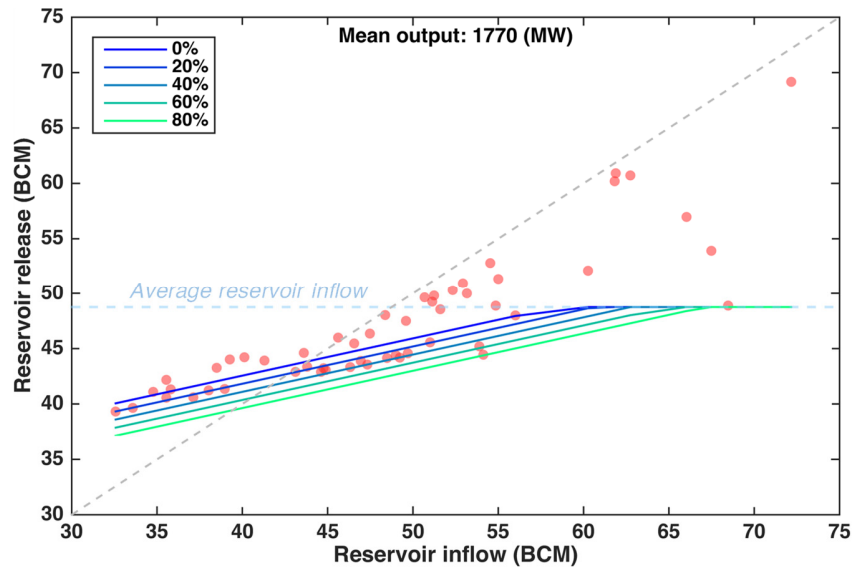
275   inflow will not be available until the last month of each year, the annual reservoir inflow forecast is used

276   instead. In this study, both a climatology inflow forecast ($Q_t'^{in}$ set as the long-term average streamflow for

277   that month) and a perfect inflow forecast ($Q_t'^{in}$ set to observed reservoir inflow Q_t^{in}) are used to evaluate

278   the performance of the drought mitigation policy. To avoid adverse downstream and upstream flood

279   caused by spillage, both the monthly and annual water release will be less than the maximum reservoir

280   inflow in flood seasons and wet years.

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282   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**

285   Multi-objective optimization of GERD reservoir operating rules illustrates that there is a trade-off between

286   reservoir power generation and deviation in reservoir annual water releases (Fig. 5 (a)). More specifically,

287   GERD monthly mean power generation output is estimated at 1788, 1708, 1737, and 1707 MW for annual

288   release standard deviations of 9, 7, 6, 5, and 4 BCM, respectively. Although the reservoir operating rules

289   are not optimized for maximum annual water release, less $Std\left(Q_y^{out}\right)$ typically leads to relatively more

290   releases in dry conditions (e.g., 5th, 10th, 15th, and 20th percentiles), especially when the mean output is

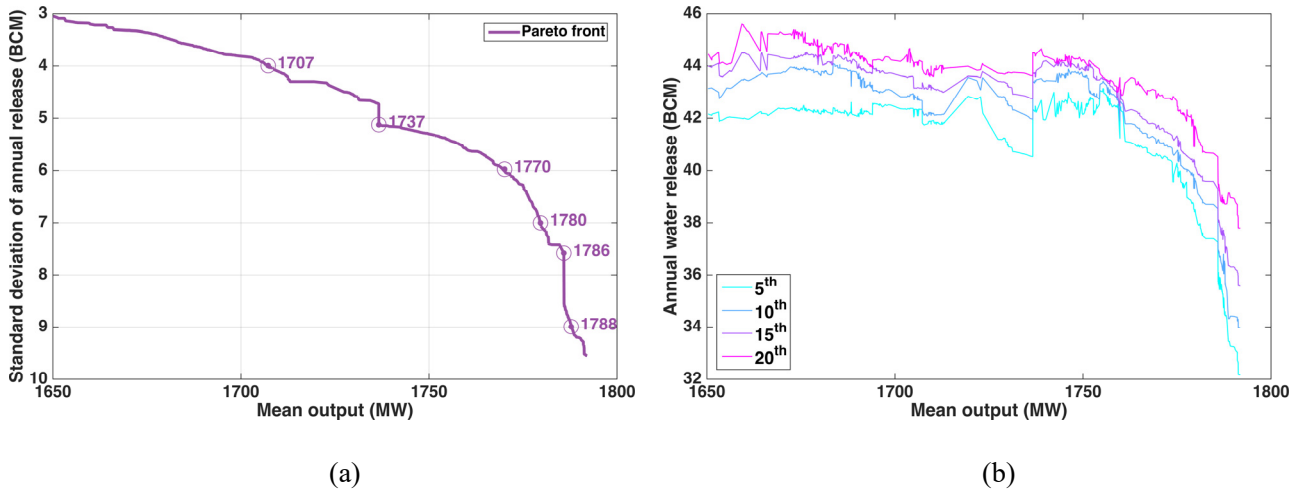
291   greater than 1750 MW (Fig. 5 (b)). Thus downstream countries may benefit more from reservoir operating

292 rules favoring smaller $Std\left(Q_y^{out}\right)$ in drought conditions; this trade-off between power generation and

293 $Std\left(Q_y^{out}\right)$ can be used to balance GERD power generation and downstream water use benefits. There also

294 exists a trade-off between $Std\left(Q_y^{out}\right)$ and other power indicators such as firm output (see Fig. S1 in

295 Appendix S1).

(a)   (b)

296 Fig. 5 Multi-objective optimization results of reservoir operating rules in terms of (a) Pareto front and (b) the

297 relationship between power generation and 5th, 10th, 15th, and 20th percentile of annual water release.

298

299 The reservoir operating rules simulation results under various mean output levels illustrates that the

300 variance of annual water release shrinks and reservoir storage declines as power output decreases (Fig. 6).

301 Although the median values of annual water release for all six output levels are approximately the same

302 (around 45 BCM), the reservoir operating rules with more output generally have lower minimum water

303 releases (Fig. 6 (a) and (b)), especially in dry periods. In general, greater reservoir storage leads to more

304 power generation (see equation (1)) and vice versa, thus the reservoir operating rules generating 1788 MW

305 of mean output produces the highest water level, and 1707 MW the lowest (Fig. 6 (d)). Also, there is a

306   clear trade-off between the variance of reservoir storage and water release (Fig. 6 (a) and (c)); smaller

307   reservoir storage variance ensures higher reservoir levels, greater water release variance, and lower

308   minimum water releases. It is worth noting that the 75th and 90th percentiles of reservoir storage are much

309   more sensitive to power output than those of water release. More specifically, the 90th percentile of water

310   release for rule types 5 and 6 are almost the same, however, the corresponding percentile of reservoir

311   storage (as well as power output) are notably different (Fig. 6 (a) and (c)). This indicates that rule type 6

312   may be inferior to rule type 5 despite of the trade-off in Fig. 5 (a). Thus, it is necessary to analyze the

313   operation results (including water release and power generation) before selecting the reservoir operating

314   rules based on the Pareto front in Fig. 5 (a).

(a)   (b)

(c)   (d)

(e)

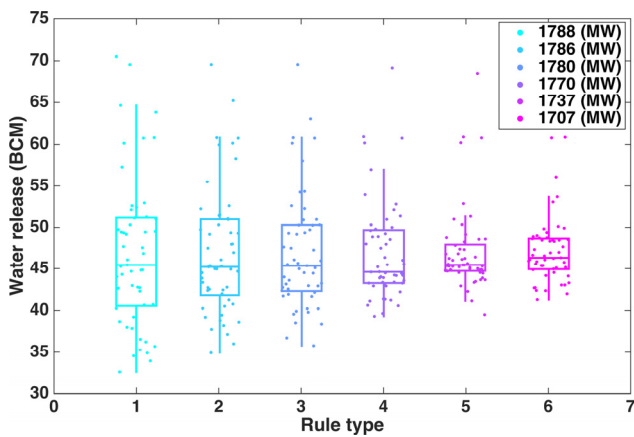
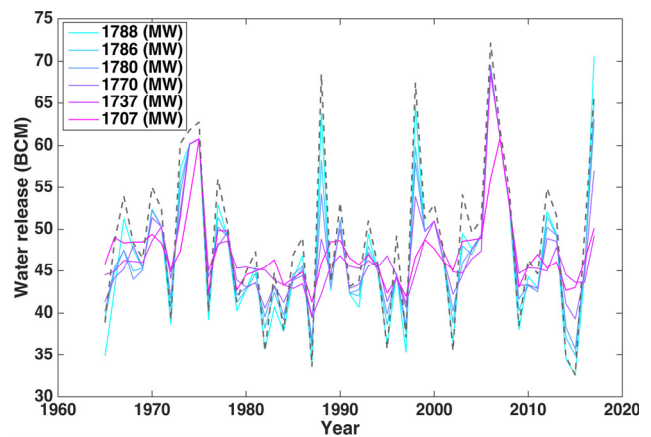
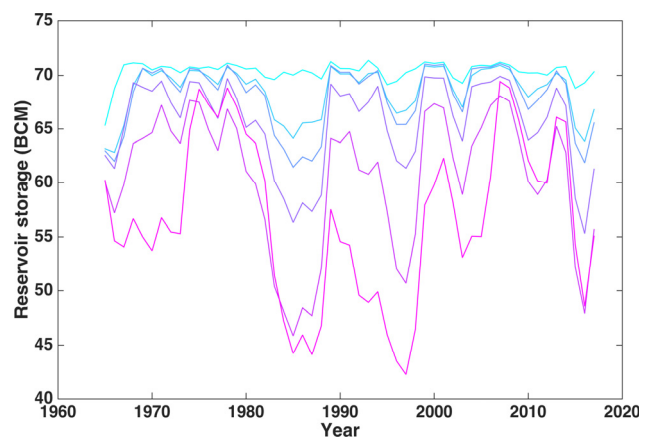
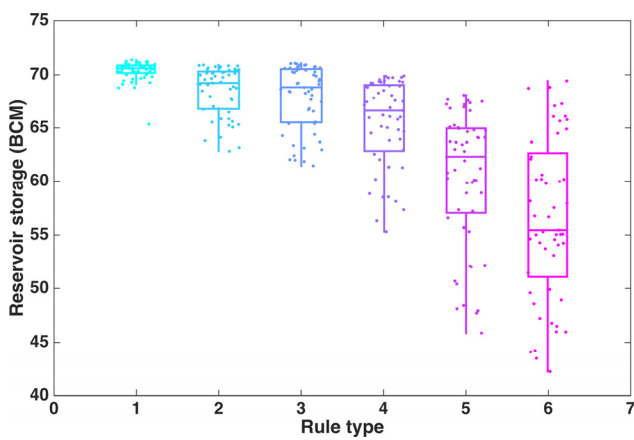
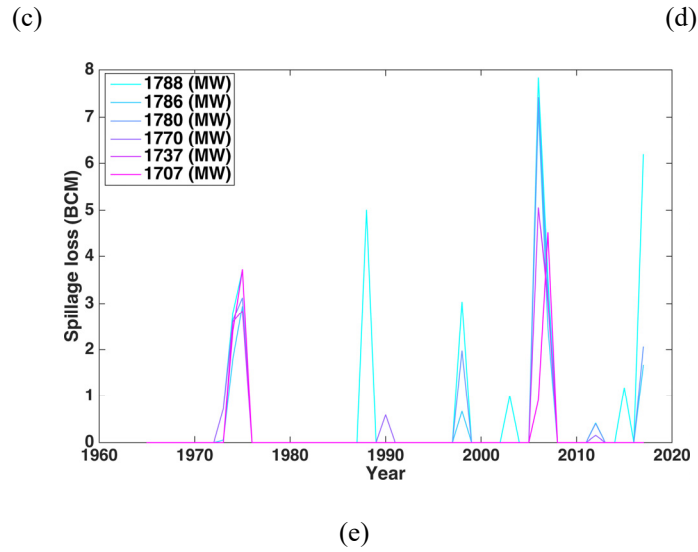



Fig. 6 Boxplots and values of annual reservoir (a)(b) water releases, (c)(d) storages, and (e) spillages for various reservoir operating rules; dished line in (b) refers to reservoir inflow.

Comparing across rule types, rules with high mean output generate more hydropower mainly in wet years. 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. 6 (b)). 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. 6 (b)) and the reservoir storage of rule type 1 is much higher than in other 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.

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 dry years (e.g., 1965 & 1997, see Fig. 6 (b)), which

329   may aggravate drought conditions. According to the relationship between annual reservoir inflow and

330   water release simulated from rule type 1, water release is less than reservoir inflow in most cases (Fig. 7

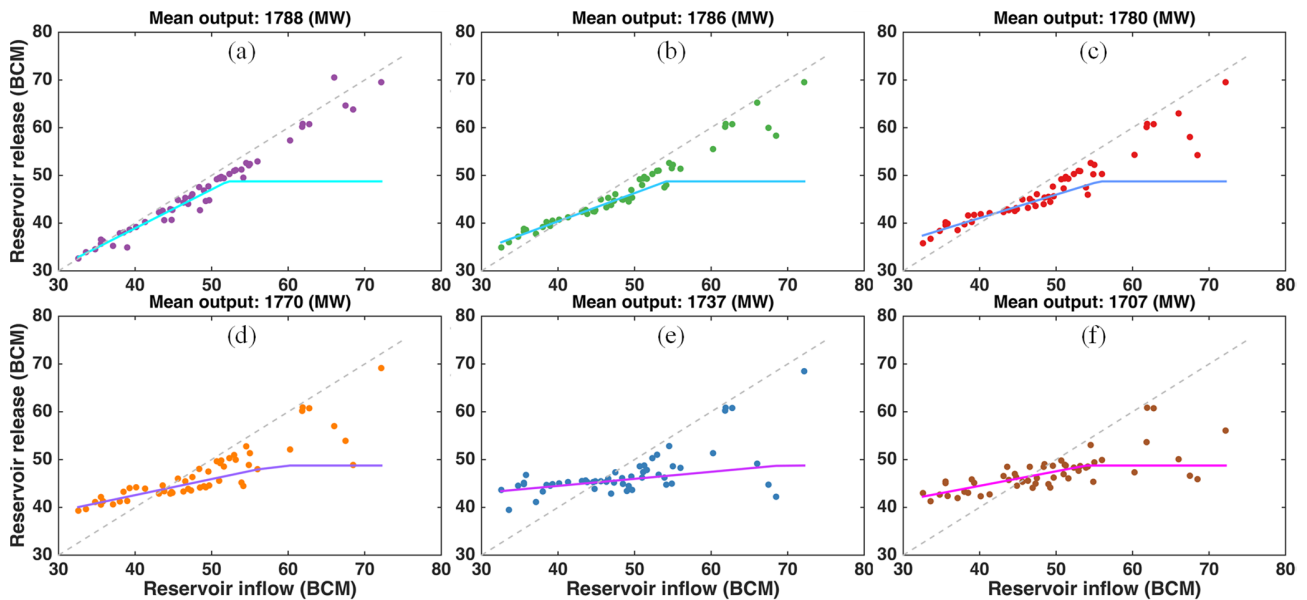
331   (a)). In comparison, rule type 3 (1780 MW) releases more water than reservoir inflow in dry years. As

332   power generation decreases further the number of years with reservoir water releases exceeding inflow

333   increases. Applying a linear regression between annual reservoir inflow and water release (see the lines

334   in Fig. 7), a drought mitigation policy (equation (10)) can be extracted to constraint annual water release

335   in reservoir operation. Rule types favoring more power generation generally produce a steeper gradient in

336   the drought mitigation policy.

337

338   Fig. 7 Relationship between annual reservoir inflow and water release (points) and the corresponding drought

339   mitigation policy (lines) for various power generation levels.

340   4.2. **Drought policy selection and analysis**

341   To select the most suitable drought mitigation policy, both the corresponding power generation and reservoir release

342   benefits in drought years may be evaluated. In this study, annual reservoir release amount and the deviation of annual

343   releases are used as proxies for downstream benefits. For example, if annual releases during drought years is greater than

344   annual reservoir inflow (or natural flow), downstream droughts are partially mitigated. In general, the statistical

345   distributions of annual reservoir inflow and releases are significantly different when reservoir operations are tailored to

346   drought mitigation. This difference is more pronounced for lower power generation levels (see Fig. S2 in Appendix S1).

347   Considering low flows, the 10th percentile of water releases increases as hydropower generation decreases, from 35.6

348   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

349   that the 10th percentile of releases is greater than the 10th percentile of annual reservoir inflow (35.8 BCM). This equates

350   to supplementing downstream flows to address drought conditions when the 10% exceedance value of annual reservoir

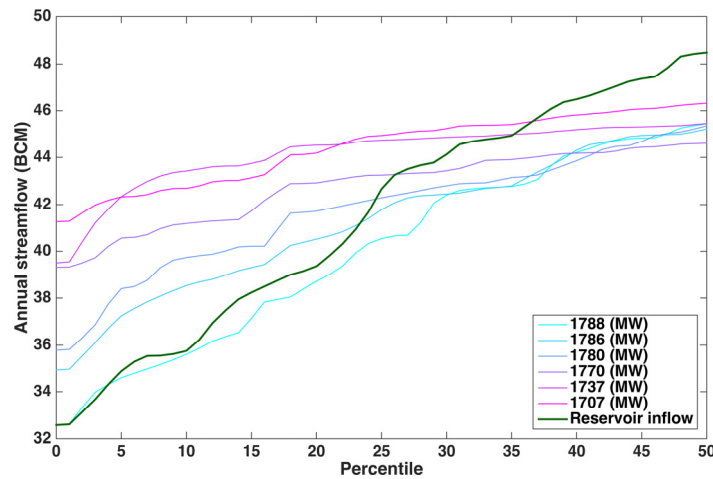
351   inflow is used as the drought threshold. Further, even when reservoir inflow is less than its 20th percentile value, water

352   releases are greater than annual reservoir inflow except for rule type 1 (Fig. 8). However, when the threshold exceeds the

353   25th percentile, only solutions based on rule type 3-6 contain annual releases surpassing inflow. These distributions (Fig.

354   8) can provide critical insights during riparian negotiations regarding trade-offs between power generation and

355   supplementing downstream flows during drought conditions. Although only six candidate solutions are illustrated here,

356   more representative solutions may be analyzed in practice.

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358   Fig. 8 Percentiles of annual reservoir inflow and water release under various power generation levels.

359   Incorporating these drought policies (Fig. 7), reservoir operating rules are optimized again for maximum

360   power generation and minimum deviation of annual release volumes, illustrating varying trade-offs for

361   drought policies 1-6 (Fig. 9). Drought policies produce similar but not exact hydropower generation as the

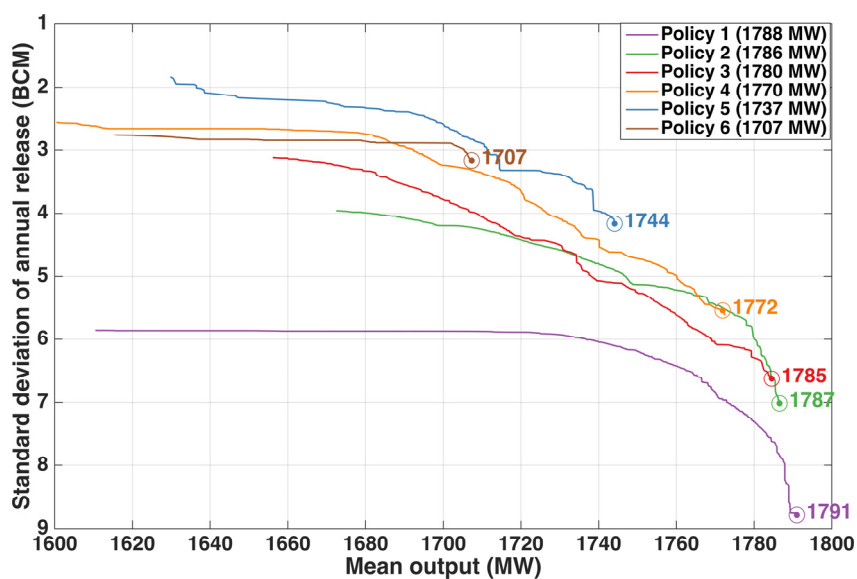
362 original operating rules (e.g. policy 1 original = 1788MW, drought = 1791MW); the standard deviation

363 of annual releases also does not change significantly. Comparing drought policies producing a high level

364 of hydropower production (e.g. moving from policy 1 to 2), a small trade-off in production (~4MW) leads

365 to approximately a 2 BCM decrease in the standard deviation of annual releases. For lesser hydropower

366 production policies (e.g. moving from policy 5 to 6), a larger difference of 37MW leads to a smaller (~1

367 BCM) change in the standard deviation of annual releases.

368

369 Fig. 9 Multi-objective optimization of reservoir operating rules with drought mitigation policies.

370 After re-optimization with the drought policy information included, greater power generation and smaller

371 values of the standard deviation of annual water releases are produced. More importantly, the re-optimized

372 rules can fully ensure minimum annual releases under different reservoir inflow levels (Fig. 10). The

373 reservoir operation results of the proposed drought policy are compared with those of conventional

374 drought/water sharing policies. A conventional water sharing policy here refers to a "guaranteed quantity"

375 or "minimum flow" strategy, i.e., GERD will guarantee a fixed volume of water release each year.

376 Compacts adopting this strategy in whole or in part include the Colorado River Compact, Arkansas River

377 Basin Compact, and Sabine River Compact, 68 Stat. 690 (1953) (McCormick, 1994;Draper, 2006). A

378 comparison (Fig. 11) indicates that the flexible drought policy proposed here can generate more power

379 than a conventional (static) drought policy with a similar statistical distribution of water releases. In

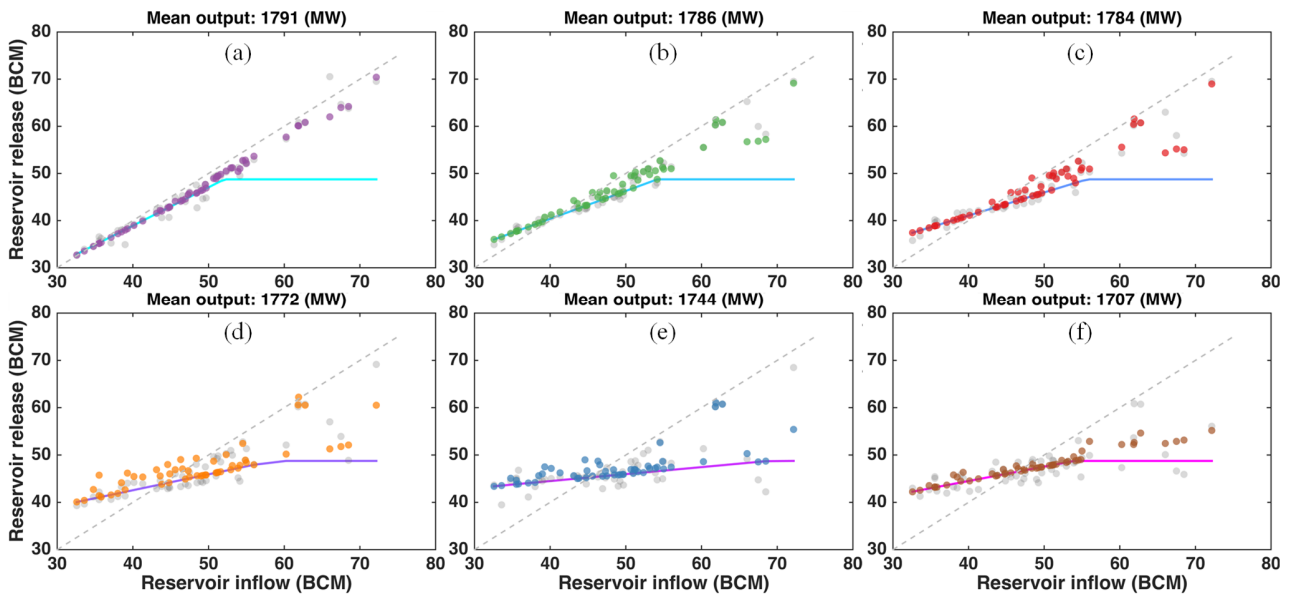
380 addition, flexible policies can better mitigate drought conditions (see the kernel distribution as well as 10th

381 percentile of water releases in Fig. 11) than static policies for similar power output levels. This is because

382 the flexible policy is derived from optimal reservoir operation results, which tends to generate more power.

383 In contrast, the static policy (which is presented as a horizontal line instead of sloped lines in Fig. 10)

384 transfers the risk of water shortages (or hydrologic variability) completely to the upstream GERD, which

385 will limit GERD's ability to produce more power.

386

387 Fig. 10 Relationship between annual reservoir inflow and releases using re-optimized reservoir operating rules;

388 drought policies represented by lines; gray points refer to the inflow and release relationship from which drought

389 policies are derived.

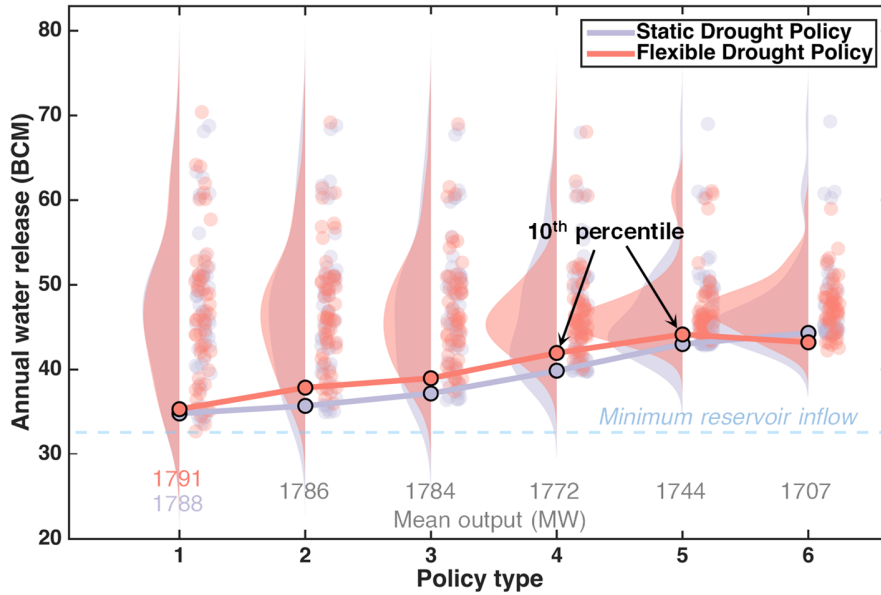



Fig. 11 Comparison of reservoir operations using flexible and static drought policies based on power generation output and water release distribution analysis. Policy type 1 refers to the comparison with a similar statistical distribution of water releases; Policy type 2-6 refer to comparisons with similar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

These re-optimized rules produce slightly more power than the original rules for equivalent standard deviation of annual release values (Fig. 12(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. 12(b)), it is feasible to base negotiations on the original rules in this case, as the expected drought policy outcomes are superior.

(a)   (b)

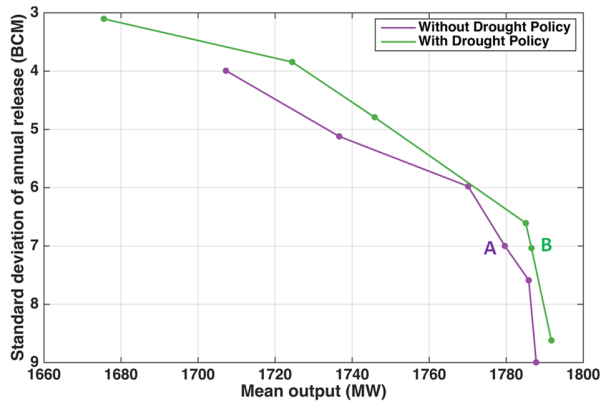
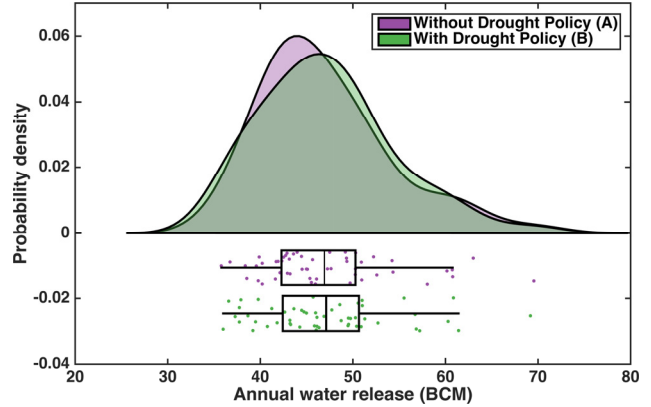



Fig. 12 (a) Pareto fronts of reservoir operation with and without drought policy; (b) boxplot of reservoir storage for solution A and B in the Pareto fronts and kernel distribution of annual reservoir water releases with and without the drought policies.

5. Conclusions

Reservoir operations in river basins will become more complex after considering diverse and potentially conflicting objectives between upstream and downstream stakeholders. 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. 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.

It is worth noting that there are limited drought periods in the historical streamflow time series, which may lead to greater uncertainty in water sharing during severe droughts and may result in underestimating

417 the impact of hydrologic variability on GERD operations. To address this, the GERD inflow record could

418 be extended by relating it to other long-term gauging stations in the Nile basin to capture more historical

419 droughts and better characterize hydrologic conditions for enhanced policy design. In addition, the trade-

420 off in objectives may be affected by land use or climate changes, and if significant, the drought policy

421 may need to be adjusted accordingly in the future. However, there will always exist a trade-off between

422 reservoir power generation and water release variability, which can be used to inform drought policy

423 design, and the linear feature of the drought policy makes it relatively easy to adjust. It is very important

424 to connect the characteristics of a water sharing policy with the trade-off between reservoir storage and

425 releases. In this study, greater variability in releases leads to a steeper gradient of the drought policy line.

426 These types of drought policy characteristics can provide guidance for stakeholders to effectively adjust

427 the water sharing policy. Thus, the interpretable drought policy proposed here can enhance the

428 understanding of water sharing and promote multilateral negotiations between upstream and downstream

429 countries.

430 This framework here is based on annual flows, however seasonal and monthly scale operations could be

431 of primary importance in smaller basins or for smaller-capacity reservoirs. Also, many other objectives

432 and constraints including firm power output, agricultural water supply reliability, and ecosystem functions

433 could be considered. Future research could explore drought-focused water sharing policies guiding

434 reservoir operations across multiple time scales simultaneously and the application of seasonal-to-sub-

435 seasonal inflow forecasts.

436 **Code and Data Availability Statement**

437   Some or all data, models, or code that support the findings of this study are available from the

438 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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