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Operations Eclipse Sequencing in Multipurpose Dam Planning

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Key Points:

- A two-part multi-objective framework is presented that jointly optimizes the sequencing and operations of multipurpose reservoirs
- One or two existing reservoirs in a river basin may dominate human-environmental tradeoffs with implications for planning new dams
- Reservoir operating policies eclipse reservoir network configurations and sequencing in balancing conflicting objectives

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract A resurgence of dam planning and construction is under way in river basins where untapped hydropower potential could meet growing energy demands. Despite calls for more comprehensive evaluation of dam projects, most dams continue to be planned with traditional methods that neglect interdependencies between planning and management and cumulative impacts of multiple new dams. Using the transboundary Zambezi Watercourse as a case study where competing demands for water, energy, and food are increasing, we contribute to a novel dam planning approach that integrates sequencing of planned reservoirs with adaptive operations. While additional hydropower capacity reduces structural energy deficits, operating polices emerge as the main driver of human-environmental tradeoffs, so much so that single-objective operating policy selection may lead to erroneous perceptions of tradeoffs across infrastructure options. Furthermore, compared to an operation and sequencing strategy that singularly maximizes hydropower, seeking compromise through operations while constructing dams early improves environmental and irrigation objectives by 50% and 80% with an 8% loss in hydropower. Alternatively, seeking compromise only through delayed dam construction yields modest environmental and irrigation improvements of 6% and 9%, respectively, with a 22% loss in hydropower. The robustness of this result is tested under an ensemble of stochastic streamflow where environmental flow and irrigation deficits are found more sensitive to operations than shifts in water availability. The predominance of operating policies is relevant for improving multi-objective dam planning in other river basins already fragmented by dams built in the twentieth century.

1. Introduction

A resurgence in dam planning and construction is under way in Southeast Asia, South America, and Africa to support increasing food and energy demands (Boulange et al., 2021; Lehner et al., 2011; Llamosas & Sovacool, 2021; Zarfl et al., 2015). As "instruments of development" providing flexible and firm hydropower, flood protection, and dependable water deliveries among other co-benefits (World Commission on Dams, 2000), large dam projects continue to attract national and regional investment. However, significant social and environmental impacts associated with large dam construction and operation (Ansar et al., 2014; Bunn & Arthington, 2002; Higginbottom et al., 2021; Molle et al., 2009; Tilt et al., 2009) elicit strong and, in some cases, paralyzing public opposition (Schulz et al., 2019). Dam planning has typically been studied and practiced using aggregate economic assessments of few alternatives with predefined operating rules (Butcher et al., 1969; Fletcher et al., 2019; Jeuland & Whittington, 2014; Montaseri & Adeloye, 1999; Peterson & Stephenson, 1991; Young & Puentes, 1969), neglecting potential tradeoffs across human-environmental objectives (Kareiva, 2012) and interdependencies between planning (i.e., size, sequence, and location) and management (i.e., operating policy) (Tian et al., 2018). Furthermore, routine site-specific dam assessments are prone to disregard cumulative impacts of multiple new dams in a river basin (Grill et al., 2015; Winemiller et al., 2016). Simplified dam planning methods are thus unconvincing or simply inadequate in demonstrating whether candidate dam projects can support multiple benefits and be robust to future uncertainties when deployed and operated in different ways.

Sequencing of water resources infrastructure expansion has been explored for urban water resource networks (Beh et al., 2014, 2015, 2017; Mortazavi-Naeini et al., 2014), water supply (Becker & Yeh, 1974; Butcher et al., 1969), and water treatment and distribution (Hinomoto, 1972; Mulvihill & Dracup, 1974), with some studies coupling expansion sequencing with water conservation (Lund, 1987; Rubinstein & Ortolano, 1984), least cost operations (Braga et al., 1985; Martin, 1987), and pricing instruments to manage demand (Dandy & Connarty, 1994). Among these, traditional dam selection and sequencing takes lead from Butcher et al.'s (1969) deduction that the rate of increasing demand, the interest rate, and the relative costs and capacities of infrastructure alternatives determine the optimal portfolio when evaluated under a minimum present cost strategy. However, as Beh et al. (2014) have shown, tradeoffs across conflicting objectives can significantly affect the optimal sequencing

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plan, tradeoffs which are in turn affected by demand and discount rates. Meanwhile, several reservoir operation studies have focused on the potential to re-operationalize existing reservoirs to adapt to changing demand and hydroclimatic conditions (e.g., Cohen & Herman, 2021; Giuliani et al., 2014), although few have combined optimization of "soft" infrastructure management with "hard" infrastructure planning. For example, Geressu and Harou (2019) showed that optimizing reservoir operations alongside expansion of the Blue Nile hydropower reservoir network reduced the strength of tradeoffs among competing objectives. Similarly, ex-post assessments by Bertoni et al. (2019, 2021) showed that had the sizing of Kariba reservoir been jointly designed with its operating policies, significant capital savings and increased robustness to changing hydroclimatology could have been realized. Thus, while computationally challenging, coupling planning of new dams with their management holds promise for sustainable and cost-effective dam design.

Here, we advance a multi-objective framework that jointly optimizes construction timing and operations of multi-purpose reservoirs to better address tradeoffs across environmental, energy, food, and economic objectives in planning how intensively to develop a large river basin (i.e., the pace and number of new dams). And whereas previous work has focused on a single reservoir's sizing and operating policy (Bertoni et al., 2019, 2021) and timing of reservoirs' construction together with their individual operating policies (Geressu & Harou, 2019), our approach optimizes the sequencing of multiple reservoirs and integrates their operations in a fully coordinated manner across the entire reservoir network. Our framework for optimal sequencing and operations differs from other approaches where triggers (Kwakkel et al., 2015) or thresholds (Herman & Giuliani, 2018) activate a sequence of adaptation actions. Instead, we first generate Pareto-efficient closed loop operating policies through Evolutionary Multiobjective Direct Policy Search (EMODPS) (Giuliani et al., 2016) for all possible adaptations (in this case each possible combination of new reservoirs); then, we optimize the year of construction for each individual dam, thus yielding Pareto-efficient sequences of dam construction that integrate optimal short-term operations concerned with intra-annual variability of demand and streamflow with long-term infrastructure investments characterized by a higher degree of uncertainty.

We apply the framework to the transboundary Zambezi Watercourse, expected to be one of the hardest-hit areas by climate change, with intensified floods and droughts that could impact the generation potential of planned hydropower plants (Kling et al., 2015). The basin's hydropower resources are considered integral for ensuring regional energy security and to achieve economic growth and alleviate poverty, goals supported by the South African Power Pool (SAPP) regional energy market to promote regional stability (Charpentier & Minogue, 1998; SAPP, 2017; World Bank Group, 2010). While controlled releases of the water system may increase tensions between upstream and downstream users (Lautze et al., 2017), a basin-wide stakeholder coordination committee established by the Zambezi Watercourse Commission (ZAMCOM) raises the prospect for coordinated reservoir operations and planning. We evaluate the resulting solutions of our framework in three ways: (a) sensitivity to operating policy selection; (b) the relative importance of sequencing versus operations in achieving compromise; and, (c) robustness of selected solutions to a synthetic streamflow ensemble of future conditions.

2. Methods

2.1. Two-Part Multi-Objective Optimization of Infrastructure Sequencing and Operations

We begin a formal description of our two-part optimization framework by defining some key variables. First, let ι be a new component to build in a reservoir network and κ a possible configuration of the network. For example, suppose there are two new reservoirs under consideration, ι^1 and ι^2; then κ^1 includes ι^1, κ^2 includes ι^2, and κ^3 includes both ι^1 and ι^2. Second, let π be an operating policy that determines the coordinated operations of the reservoir network. Therefore in our simple example, π_{κ^1} defines the operations of ι^1, π_{κ^2} the operations of ι^2, and π_{κ^3} the coordinated operations of ι^1 *and* ι^2. The sequencing problem is to decide which reservoirs to build and when to build them, thus determining how the reservoir network evolves from the initial condition κ^0 (i.e., no new reservoirs) to the final network κ^F. The operation problem is to determine how to operate each network κ^i along the pathway.

Uniting infrastructure sequencing and operations into a single problem of finding Pareto-optimal pathways P^* with respect to multiple objectives $\mathbf{J}_P$ can thus be formulated as follows:

$$\begin{aligned} & P^* = \arg\min_P \mathbf{J}_P \\ \text{where} \quad & P = |\mathcal{K}, \Pi^*(\mathcal{K})| \qquad (1) \\ \text{and} \quad & \mathbf{J}_P = |J^{\inf}_{\mathcal{K}}, J^{op}_{\mathcal{K},\Pi(\mathcal{K})}| \end{aligned}$$

- where $\mathcal{K} = [\kappa_\tau^0, \kappa_\tau^1, \ldots, \kappa_\tau^F]$ specifies the timings τ of changing the reservoir network to κ^i (as described above);
- $\Pi^*(\mathcal{K})$ is the set of Pareto optimal operating policies π_{κ^i} for all reservoir networks $\kappa^i \in \mathcal{K}$;
- $J_{\mathcal{K}}^{\text{inf}}$ are the infrastructure planning objectives which are a function of the infrastructure sequencing;
- and $J_{\mathcal{K},\Pi(\mathcal{K})}^{op}$ are the operational objectives which are a function of the infrastructure sequencing and operating policies.

The problem in Equation 1 is dynamically constrained by the state transition function $\mathbf{x}_{t+1} = f_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1})$, in which sequential decisions $\mathbf{u}_t$ (e.g., reservoir releases and irrigation abstractions) are determined by the operating policy based on the current state vector (e.g., reservoir storage), that is, $\mathbf{u}_t = \pi_{\kappa^i}(t, \mathbf{x}_t)$, and evolves under the influence of stochastic external drivers ε_{t+1} (e.g., reservoir inflow). A detailed description of the reservoir system simulation model developed for our case study is provided in Text S1 in Supporting Information S1.

2.2. Solution Method and Constraints

As formulated in Equation 1, an optimal "pathway" is a vector of timings that evolve a reservoir network to new configurations (by adding one or more reservoirs) together with a set of operating policies for each reservoir network along the pathway. The implication is that multiple optimal operating policies must be found to fully describe a pathway, and that each operating policy is active only during the period for which its reservoir network is in place. Solving Equation 1 within a single optimization routine would have the challenge of optimizing multiple operating policies over varying horizons and portions of a stochastic time series. Therefore, we optimize the operating policies for each possible reservoir network separately—where the policy inputs and parameters change for each network—and over a single, stationary representation of external drivers.

Accordingly, we decompose Equation 1 into a two-part optimization routine as depicted in Figure 1. The Part 1 optimization routine is conducted over a historical scenario $\bar{w}$ of external drivers and generates archives of the Pareto efficient operation policies π_{κ^i} for each possible reservoir network via Evolutionary Multiobjective Direct Policy Search (EMODPS) (Giuliani et al., 2016), a reinforcement learning approach that combines direct policy search, non-linear approximating networks, and multi-objective evolutionary algorithms (MOEAs). The Part 2 optimization routine is conducted over a future nominal scenario $\hat{w}$ of external drivers and generates a set of Pareto efficient construction timings τ for the reservoirs under consideration using Borg MOEA only (see Text S2 in Supporting Information S1 for a description of our MOEA experimental settings). If the Part 1 operating policy optimization had been conducted with future hydrology, then performance would be slightly improved on all objectives. However, optimizing operations to a future scenario would assume an optimistic case where reservoir operators recognize and immediately coordinate their reaction to changes in the distribution of basin inflows. Although it is somewhat pessimistic to optimize operations to historical hydrology, the cyclostationary, closed-loop control policies include storage state feedbacks on release decisions, which implies that they are adaptable to changes in external conditions (e.g., inflows).

In addition, we place two constraints on the second optimization routine.

- **Constraint 1**: Dam construction cannot be reverted, which is realistic given the low likelihood of dismantling hard infrastructure over the planning horizon.
- **Constraint 2**: Selection of π_{κ^i} from the archive of Pareto efficient operating policies for each candidate reservoir network configuration is based on a single preference adopted for the entire planning horizon. When a new dam is built, the operating policy is updated to one that incorporates new infrastructure but maintains the initially adopted preference. We constrain the operating "preference" in two ways: (a) the best performing solution on a single objective (i.e., an extreme operating preference); and (b) the solution closest to the ideal point of all objectives in normalized space (i.e., a compromise preference).

Finally, we test the sensitivity of the two-part joint optimization framework in two ways. First, we conduct two additional Part 2 sequencing optimizations with alternate preferences for the operating policy selection (Section 4.4). Second, we conduct a robustness evaluation of two sequencing solutions by re-simulating them under (a) a 450-member synthetic ensemble of plausible future streamflow conditions and (b) an alternate operating policy set from the Part 1 optimization that achieves compromise on all operating objectives (Section 4.5).

2.3. Parameterization of Infrastructure Operating Policies

The operating policy π_κ subsumes a reservoir release policy $\rho_{\theta(\kappa)}$ and irrigation diversion policy $\theta_\omega(\kappa)$ parameterized within the space of parameters $\theta \in \Theta$. The reservoir release policy $\rho_{\theta(\kappa)}$ is parameterized according to

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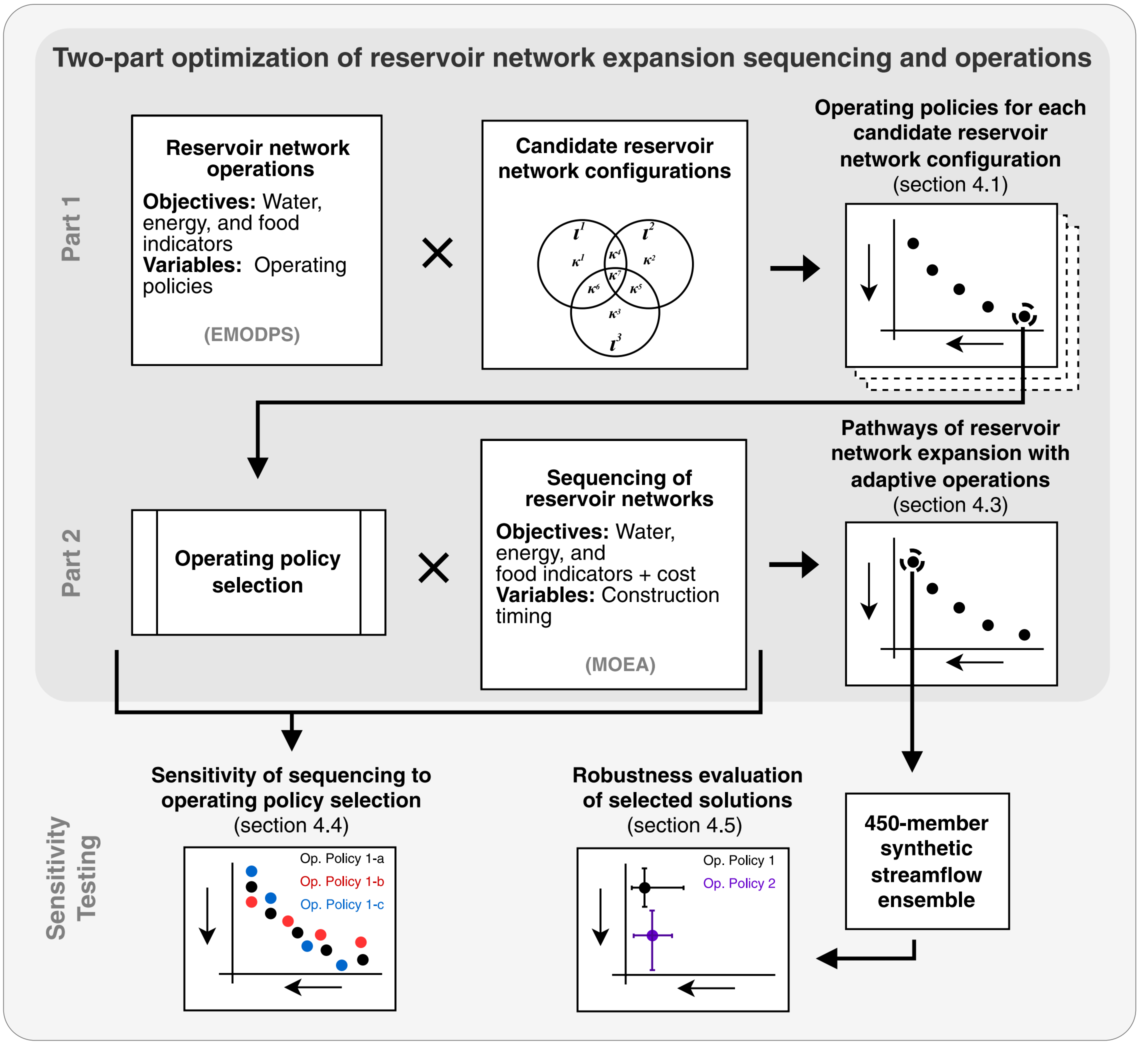

Figure 1. Workflow of the two-part joint optimization of infrastructure operations and sequencing. In Part 1, archives of Pareto-optimal operations are found for each possible reservoir network configuration. Part 2 searches for Pareto optimal build timings of the candidate reservoirs having adopted an operating policy found in Part 1.

nonlinear approximating networks, and, in particular, non-convex Gaussian radial basis functions (RBFs). The kth release decision in the R-dimensional vector $\mathbf{u}_t$ is calculated as follows:

$$u_t^k = \delta_k + \sum_{i=1}^{N} w_{i,k}\varphi_i(I_t) \tag{2}$$

where N is the number of RBFs $\varphi(\cdot)$, δ_k is a constant linear parameter, and $w_{i,k}$ the non-negative weight of the ith RBF ($w_{i,k} \geq 0, \forall i$). The inclusion of δ_k improves the policy in reservoir operation settings by permitting a specific target release which can be optimal for meeting constant water demands or target hydropower releases equal to turbine capacities. A single RBF is defined as follows:

$$\varphi_i(I_t) = \exp\left[-\sum_{j=1}^{M} \frac{\left[(I_t)_j - c_{j,i}\right]^2}{b_{j,i}^2}\right] \tag{3}$$

where M is the number of policy inputs I, and c and b are the M-dimensional center and radius vectors of the ith RBF. The centers of the RBF must lie within the bounded input space and the radii must strictly be positives, that is, using normalized variables $c_i \in [-1, 1]$ and $b_i \in (0, 1]$. The reservoir operating policy parameter vector θ is therefore defined as $\theta = [\delta_k, c_{j,i}, b_{j,i}, w_i]$ with $i = 1, \ldots, N, j = 1, \ldots, M, k = 1, \ldots, R$. Policy inputs include

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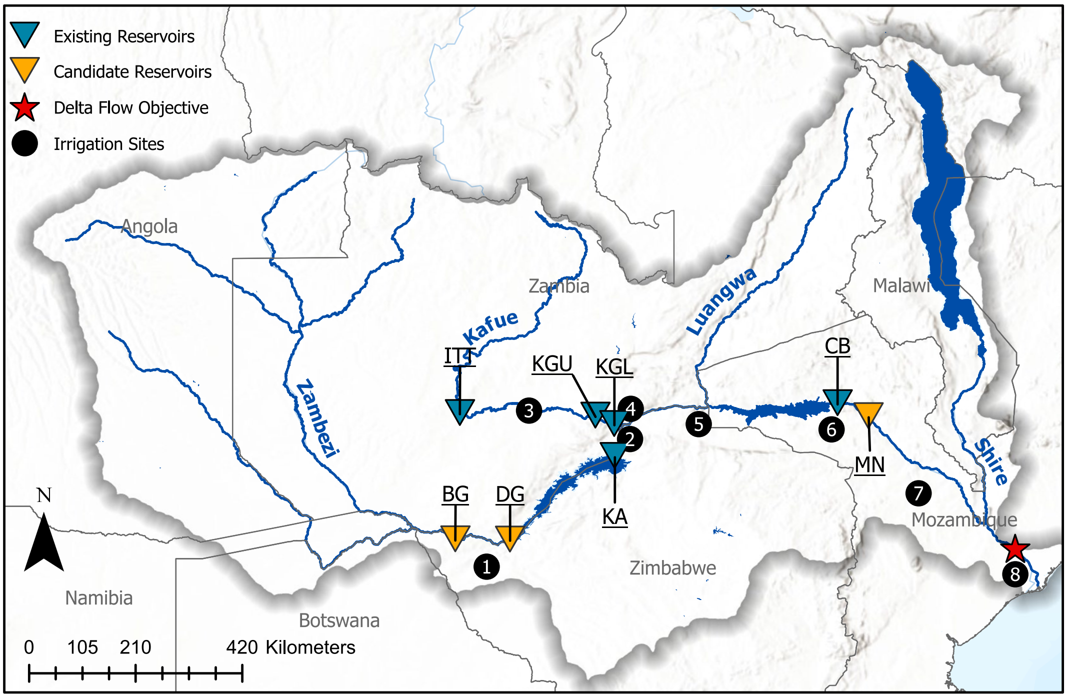

Figure 2. Map of the Zambezi River Basin with locations of major existing and planned reservoirs, irrigation districts, and the Zambezi Delta outflow location of environmental and ecosystem service importance. Reservoir key: Itezhi-Tezhi (ITT); Kafue Gorge Upper (KGU); Kafue Gorge Lower (KGL); Batoka Gorge (BG); Devils Gorge (DG); Kariba (KA); Cahora Bassa (DB); Mphanda Nkuwa (MN).

storage of each reservoir, total basin inflow of the previous month, and time (current month of the year). Thus, the multi-dimensional reservoir operating policy assumes full coordination of all reservoirs in the basin.

As for the irrigation policy $\theta_{\omega}(\kappa)$, water for the *id*th irrigation district (ω^{id}) is abstracted from the river according to a non-linear hedging rule (Celeste & Billib, 2009) as follows:

$$\omega_{t+1}^{id} = \begin{cases} \min\left(q_{t+1}, \upsilon_t^{id} \cdot \left[\frac{q_{t+1}}{h^{id}}\right]^{m^{id}}\right) & if\ q_{t+1} \le h^{id} \\ \min\left(q_{t+1}, \upsilon_t^{id}\right) & else \end{cases} \tag{4}$$

where q_{t+1} is the volume of water available in the river channel at the diversion point, υ_t^{id} is the monthly water demand, and h^{id} and m^{id} are the parameters regulating the diversion channel. The irrigation policy parameters are optimized together with the reservoir operating policy parameters in the EMODPS optimization.

3. Case Study

This section covers the formulation of operation and infrastructure planning objectives and external drivers for the two-part optimization candidate reservoir sequencing and operations for the Zambezi Watercourse. Additional case study details may be found in Texts S1 (reservoir simulation model), S3-5 (hydropower and irrigation demands and hydrology), and S8 (stakeholder objectives) in Supporting Information S1.

The map in Figure 2 shows the major candidate reservoirs and human-environmental indicators of the Zambezi Watercourse: the hydrologic network, locations of existing and planned multi-purpose reservoirs, eight irrigation districts representative of existing and projected agricultural development, and the Zambezi Delta outflow location of environmental and ecosystem service importance. An estimated one-third of the basin's 40,000 MW hydropower potential has been realized by existing projects (Spalding-Fecher et al., 2016, 2017; World Bank Group, 2010), whose combined evaporation represents the single largest consumptive use in the basin and whose seasonal operations have substantially altered streamflow regimes over the twentieth century (Beilfuss, 2010; Beilfuss & Dos Santos, 2001). Together the three candidate reservoirs—Batoka Gorge (BG), Devils Gorge (DG),

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and Mphanda Nkuwa (MN)—would increase the basin's hydropower production capacity by 4.1 GW (+37%) and active storage capacity by 10.6 km^3 (+8%) for a total construction cost of \$9.65 Bn.USD (see Table S1 in Supporting Information S1 for characteristics of existing and planned reservoirs).

3.1. Operational and Infrastructure Planning Objectives

From over three dozen metrics identified by stakeholders in the Zambezi Watercourse as part of a participatory planning process (see Text S8 in Supporting Information S1), three design indicators representing water, energy, and food nexus components at the basin scale were selected for the optimization of reservoir operations and sequencing: environmental flow deficit, hydropower deficit, and irrigation deficit. In addition, net present cost (NPC) was included in the sequencing optimization to signal tradeoffs with the three design indicators. Whereas the three design indicators change with both sequencing and operating policies ($J^{op}_{\mathcal{K},\Pi(\mathcal{K})}$ in Equation 1), NPC is the only planning objective that depends solely on the infrastructure sequencing ($J^{\inf}_{\mathcal{K}}$ in Equation 1).

3.1.1. Environmental Flow Target

A flow deficit located at the Delta (the most downstream location in the Zambezi Watercourse) was used as a proxy for environmental health and ecosystem services dependent on maintenance of a more natural flow regime:

$$J^{Env} = \frac{1}{H}\sum_{t=0}^{H}\left(\max\left(T_t^{env} - r_{t+1}^{env}, 0\right)\right)^2 \tag{5}$$

where T_t^{env} is the target flow to be satisfied and r_{t+1}^{env} is the actual flow governed by upstream reservoir release decisions and irrigation diversions. The sum of squared flow deficits are averaged over all time steps in planning horizon H. We set T_t^{env} equal to 7,000 m^3/s for the months of February and March (zero for all other months), a magnitude and timing widely adopted in the literature (Giuliani & Castelletti, 2013; Tilmant et al., 2010, 2011).

While the environmental flow measure approximates several objectives within a single design indicator for the Delta, it is not a proxy for hydrologic alteration in ecologically sensitive upstream areas. For these sensitive upstream stream locations, we include minimum environmental flow requirements as first-order constraints on system flow management. At Victoria Falls, a run-of-river hydropower plant above Kariba reservoir, 250 m^3/s are left in the river every month and cannot be diverted to be turbinated. For Kafue Flats, the upstream Itezhi-Tezhi reservoir is forced to release at least 40 m^3/s every month, except for March when 315 m^3/s are needed to maintain the natural flooding pattern.

3.1.2. Hydropower Deficit

The design indicator representing the energy sector is formulated as annual average hydropower production deficit:

$$J^{Hyd} = \frac{1}{N}\sum_{t=0}^{H}\left|T_t^{HP,i} - HP_{t+1}^{i}\right|_{i=1,\dots,I} \tag{6}$$

where T_i^{HP} is the target production and HP_{t+1}^{i} is the actual hydropower production at the ith hydropower plant, and N is the number of years in the planning horizon H. Hydropower production is calculated according to standard formula for power generation: $\eta^i g\gamma \bar{h}_t^i q_{t+1}^{turb,i}$ where η is the turbine efficiency, $g = 9.81$ m/s^2 is the gravitational acceleration, $\gamma = 1000$ kg/m^3 is the water density, $\bar{h}_t^i$ [m] is the net hydraulic head, and $q_{t+1}^{turb,i}$ [m^3/s] is the turbinated flow. The hydropower production targets $T_t^{HP,i}$ were developed using TEMBA, a model of the South African power grid model built with the open source modeling system OSeMOSYS (Taliotis et al., 2016). TEMBA optimizes the energy production mix to satisfy energy demand at the power pool level and thus represents a reasonable estimate of the allocated demand to each power plant source. In accordance with the Zambezi River Basin master plan (ZAMCOM, 2019) and considering that all the hydropower plants are connected to the SAPP, the hydropower production objective is aggregated at the basin-wide scale thus neglecting national strategies.

3.1.3. Irrigation Deficit

The design indicator representing food security is formulated as a normalized irrigation deficit:

$$J^{Irr} = \frac{1}{H}\sum_{t=0}^{H}\left(\frac{\max\left(T_t^{irr,id} - \omega_{t+1}^{irr,id}, 0\right)}{T^{irr,id}}\right)^2_{id=1,\dots,ID} \tag{7}$$

where $T_t^{irr,id}$ and $\omega_{t+1}^{irr,id}$ are irrigation water demand and actual abstraction for the *id*th irrigation district, respectively. The normalized formulation weighs irrigation district deficits equally regardless of the magnitude of their demands which allows districts to be grouped within the same design indicator without favoring one district over another.

3.1.4. Net Present Cost

The NPC of capital is included in the sequencing optimization problem according to the following discounted capital expenditure equation:

$$J^{NPC} = \sum_i \sum_t \left[\left(\frac{1}{(1+\gamma)^t} - d_H \frac{\Delta life_t^i}{lifespan} \right) \times \kappa^i \right] \quad (8)$$

where γ is the real discount rate, κ^i is the capital expenditure of the *i*th candidate reservoir, $\Delta life_t = lifespan - (H - t)$ and $d_H = \frac{1}{(1+\gamma)^t}$ where H is the simulation horizon and t is the year of construction. We use a discount rate of 10% which is consistent with the World Bank's project-level financial risk analysis conducted in Cervigni et al. (2015).

3.2. External Drivers

As described in the solution method to problem 1, the Part 1 EMODPS operations policy optimization is conducted over a single historical scenario of external drivers. The historical data include the observed hydrology for the major basin inflow locations covering the 1986–2005 period at a monthly time step and socioeconomic (i.e., irrigation and hydropower demand) time series for a single reference year which is repeated every year of the simulation. The Part 2 MOEA sequencing optimization is conducted over a single nominal future scenario covering a 2020–2060 period of analysis. As the basis for growing hydropower and food demands, population growth rates were collected from (United Nations DESA, 2018) and aligned with the "middle of the road" Shared Socio-economic Pathway (SSP) 2 (Riahi et al., 2017) (see Texts S3 and S4 in Supporting Information S1). In SSP2, the future evolves following trends from the past century. Richer countries in the basin such as Angola, Tanzania and Botswana keep growing at a higher pace than their less developed counterparts such as Malawi and Namibia. As the basis for changes in hydrology and crop water demand, climate projections of precipitation and temperature were statistically downscaled from a regional climate model of the CORDEX archive (Giorgi et al., 2009) forced with Representative Concentration Pathway (RCP) 4.5. Streamflows were developed using the Hydrologiska Byrans Vattenbalansavdelning (HBV) (Lindström et al., 1997) conceptual hydrologic model while crop water demand was developed using the AquaCrop model (Steduto et al., 2009) (see Text S5 in Supporting Information S1).

4. Results

4.1. Operating Policy Tradeoffs

Using historical hydrology and irrigation and energy demands, archives of Pareto-efficient operating policies were generated for eight candidate reservoir network configurations (κ^{1-8}): the existing (Base) reservoir network together with seven possible expansions that include one or more of the three planned reservoirs (ι^{1-3}; see Table S2 in Supporting Information S1). The obtained Pareto optimal solutions in Figure 3 show similar operating policy-driven tradeoffs across the candidate reservoir network configurations. The strongest conflict is between the hydropower deficit and the environmental flow deficit. Irrigation performance can be exchanged with the environmental deficit or with the hydropower deficit at roughly all levels of performance (i.e., moving horizontally or vertically across Figure 3), with the largest irrigation deficits occurring at the lowest hydropower deficit levels. The candidate reservoir network configurations share a comparable range of irrigation deficit of $\approx 0 - 2.0$ and environmental deficit of $\approx 0.1 - 3.8 \times 10^6$ [m^3/s]^2, and all reach a minimum achievable hydropower deficit at an environmental deficit of $\approx 3 \times 10^6$ [m^3/s]^2.

Overall, the Pareto-optimal operating policy archives suggest that none of the candidate reservoir network configurations constrains the best possible environmental and irrigation performance relative to the Base network. The single major difference in operating policy-driven tradeoffs is shown with the inclusion of Mphanda Nkuwa reservoir (network configurations along the bottom row of Figure 3) which increases the strength of the environmental-hydropower tradeoff relative to the two planned upstream reservoirs Batoka Gorge and Devils

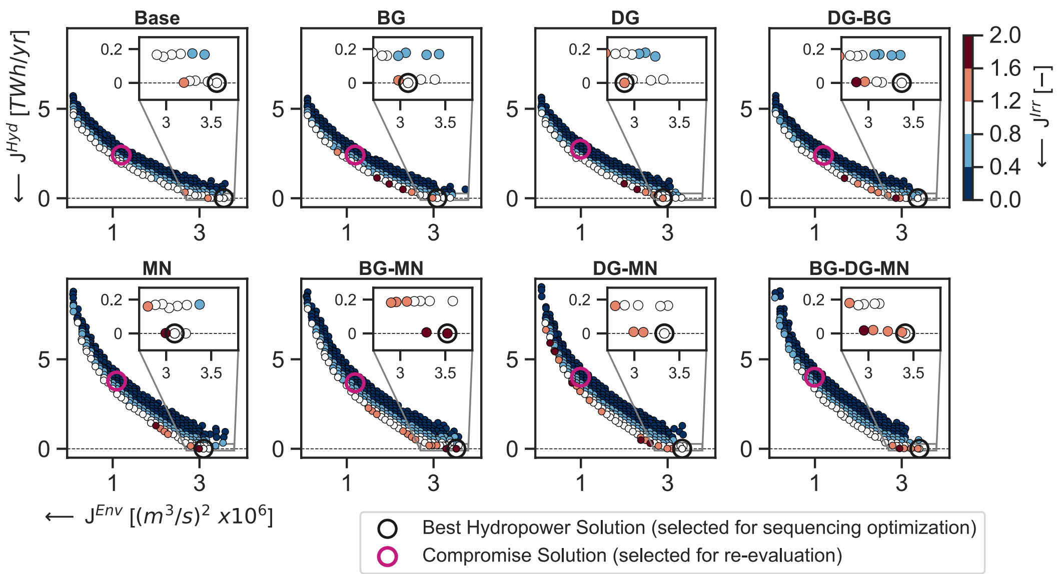

Figure 3. Pareto reference sets of operating policies for the existing (Base) and seven candidate reservoir network configurations which include one or more of the three planned reservoirs (reservoir key: Batoka Gorge (BG); Devils Gorge (DG); Mphanda Nkuwa (MN)). To facilitate cross-comparison of the reference sets, the hydropower deficit (J^{Hyd}) is plotted relative to the minimum deficit achieved under a given reservoir network configuration. The "best hydropower" solution selected for the sequencing optimization is indicated with an open black circle on the main and inset plot. The "compromise" solution (closest to ideal point in normalized objective space) is identified with an open pink circle.

Gorge. Mphanda Nkuwa's amplification of the hydropower-environmental tradeoff is largely due to its location at the lowest point in the reservoir network and just above the Delta. We explore operational dynamics driving these tradeoffs in the next section.

4.2. Operational Dynamics

Reservoir storage and release dynamics of the Pareto reference set operating policies for the Base reservoir network and full build-out of planned dams (BG-DG-MN) are shown in Figure 4. Beginning upstream on the Zambezi at Kariba reservoir, operations do not vary widely over the Pareto set of policies for both Base and BG-DG-MN. Kariba's annual strategy shows storage buildup and increasing releases through the peak inflow period followed by releases from storage through the drier season, thereby shifting the natural runoff regime forward by 1 month and dampening seasonal variability. For the BG-DG-MN network, Devils Gorge reservoir further dampens seasonal variability with its 7 km^3 of active storage sustaining more constant hydropower generation throughout the year. Like Kariba, Devils Gorge operating policies are nearly identical across the Pareto sets. Kariba takes advantage of Devils Gorge's smoothing of streamflow variability by increasing releases in the dry season for greater hydropower generation. With its smaller storage capacity, Batoka Gorge reservoir does little to affect the Zambezi's streamflow, operating closer to a run-of-river hydropower plant.

Moving to the Kafue river tributary, Itezhi-Tezhi and the two Kafue Gorge reservoirs exhibit more operating variability across the Pareto reference sets for both the Base and BG-DG-MN. Itezhi-Tezhi has the smallest operating policy differences, maintaining its primary purpose as a regulator for hydropower-generation at Kafue Gorge. Distinct operating differences arise for Kafue Gorge between policies tailored toward reducing hydropower or environmental deficits. When operating to minimize hydropower deficits, Kafue Gorge Upper accumulates storage from January through May to support higher dry season releases. But when operating toward the environmental objective, Kafue Gorge Upper delays fill up until April, allowing wet season runoff to pass through and contribute to the Delta flow target. Kafue Gorge Lower's active storage space is highly constrained, which contributes to its limited policy variability and reflection of Kafue Gorge Upper's release profile. Kafue Gorge Upper and Lower's operating policy tradeoffs are largely unchanged between the Base to the complete build-out of planned dams, although the compromise policy shifts toward the best environmental policy and the best hydropower policy favors higher releases and lower storage volumes. In fact, cyclostationary operations of

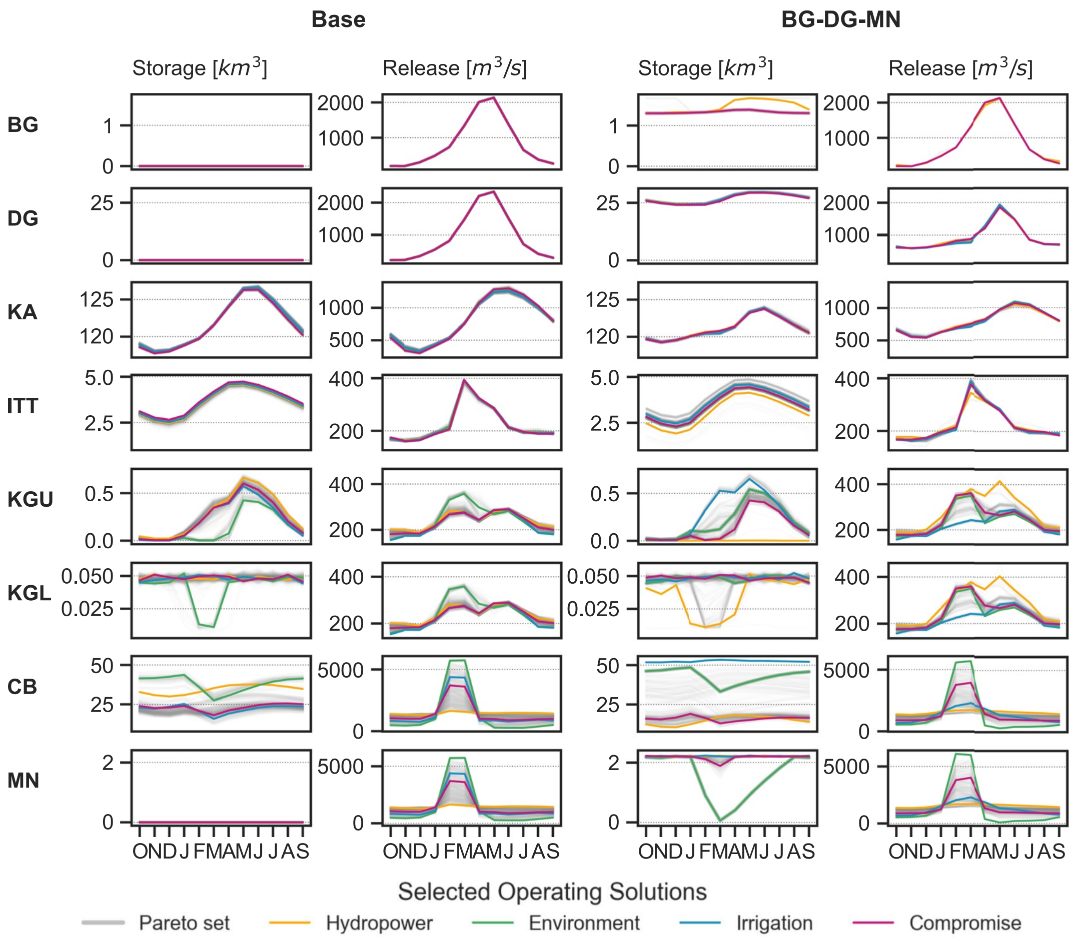

Figure 4. Cyclostationary storage and release dynamics of Pareto optimal operating policies obtained for the Base network (left panel) and complete build-out of planned dams ("BG-DG-MN") (right panel). Policies maximizing one of hydropower, irrigation, or environmental performance and the compromise policy (best possible performance over all three objectives) are highlighted.

the second-best hydropower policy—which has only a 0.02% higher average hydropower deficit—are unchanged from the Base network, however, the distribution of monthly hydropower deficits is different between the two operating regimes (see Figure S5 in Supporting Information S1). The best hydropower policy trades higher, infrequent deficits at KGU and KGL for lower, frequent deficits at CB and MN. Meanwhile, the second-best hydropower policy trades higher, frequent deficits at CB and MN for lower, infrequent deficits. The equifinality in the two alternative operational strategies is likely due to MN's additional hydropower generating potential.

Moving downstream below the confluence of the Zambezi, Kafue, and Luangwa tributaries, Cahora Bassa reservoir exhibits the greatest operating policy variability across the Pareto sets and is therefore the predominant controller of the environmental, hydropower, and irrigation tradeoffs for both the Base and BG-DG-MN. To minimize hydropower deficits, Cahora Bassa maintains almost constant year-round releases. In the BG-DG-MN network, Cahora Bassa exhibits the same cyclostationary drawdown cycle as in the Base network but drops average storage by ≈25 km^3. For the Best Environment operating policy, Cahora Bassa accumulates storage through the dry season (to the obvious detriment of hydropower production from lower releases) to support higher Feb-Mar releases for meeting the Delta flow objective. Although Mphanda Nkuwa can provide a slight boost to Feb-Mar releases of the Best Environment operating policy by drawing on its ≈2 km^3 of storage, the reservoir mostly reflects the cyclostationary policies of Cahora Bassa, thus amplifying the environmental-hydropower tradeoff seen in Figure 3.

In sum, whereas Cahora Bassa's operation—with minor contribution of the Kafue tributary reservoirs—controls the tradeoff between Delta environmental flow and hydropower production, addition of upstream reservoirs

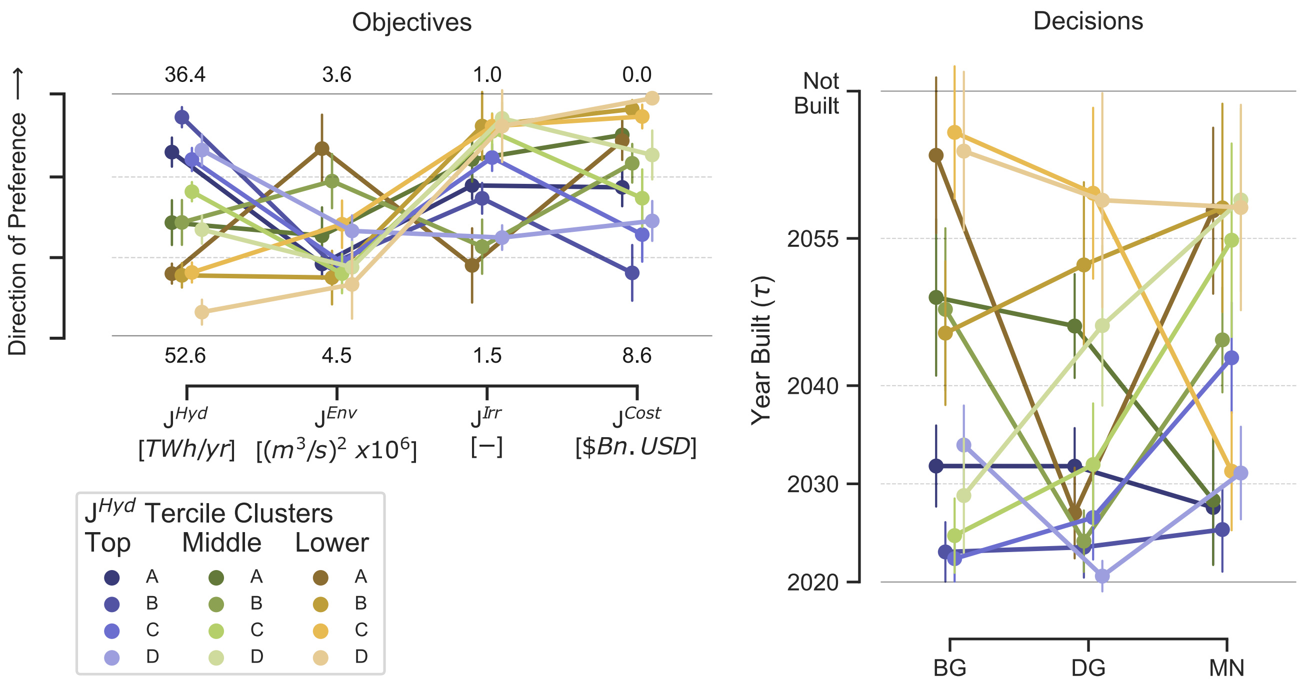

Figure 5. Clustered Pareto reference set objectives and decisions (timing) of reservoir sequencing using the best hydropower operating policy. Lines represent the mean cluster value and error bars show the standard deviation within the cluster. The best and worst real-valued objective performance is noted at the top and bottom of the plot of normalized objectives.

Batoka Gorge and Devils Gorge does little to affect tradeoffs. The addition of Mphanda Nkuwa exacerbates the hydropower-environmental conflict due to the additional hydropower losses incurred to operate toward the Delta flow target; however, Mphanda Nkuwa's Pareto-optimal policies reflect Cahora Bassa's downstream control. In other words, if Cahora Bassa is operated to maximize hydropower, there is no way for Mphanda Nkuwa to operate toward the environmental flow target, with Cahora Bassa thus remaining the predominant controller of the environmental-hydropower tradeoff. The operational dynamics indicate how Pareto-optimal policies update to take advantage of additional upstream storage regulation (i.e., Devils Gorge and Lake Kariba) while having little effect on the major downstream control of tradeoffs.

4.3. Optimization of Infrastructure Pathways

Our optimization of reservoir sequencing and operations (i.e., "pathways") relies on the archives of Pareto-efficient operating policies (see Figure 3). Because current system operations are skewed toward hydropower generation, the extreme "Best Hydropower" operating policy for each infrastructure configuration is selected as a proxy for an ideal rule curve aligned with current preferences of Zambezi Watercourse stakeholders.

To support interpretability of the Pareto-optimal pathway solutions, we extract feature groups from the Pareto reference set having segmented solutions into three equal-spaced terciles of higher, middle, and lower hydropower deficits (J^{Hyd}). For each J^{Hyd} tercile, we apply principal component analysis (PCA) to the combined objectives and decisions (a total of seven dimensions) and run k-means clustering with four clusters on the first three principle components which explain ≈90% of the variability (see Text S9 in Supporting Information S1). The cluster mean and within-cluster standard deviation of objectives and reservoir build timing decisions are shown in Figure 5.

Overall, the strongest tradeoff is between NPC and hydropower. Cluster B of the top-J^{Hyd} tercile is the most costly set of pathways which build all three planned reservoirs within 5 years. Conversely, Cluster D of the lower-J^{Hyd} tercile group waits until the last 5 years of the planning horizon to selectively build one or both of Devils Gorge and Mphanda Nkuwa (both of lower capital expense than Batoka Gorge) or in many cases no reservoir at all, thus representing the least costly set of pathways with the highest hydropower deficits. Clusters with the greatest hydropower performance for the least cost relative to a J^{Hyd} tercile include: Cluster B in the lower J^{Hyd} tercile, which is selective of an earlier Batoka Gorge build followed by Devils Gorge and Mphanda Nkuwa; Cluster A of the middle J^{Hyd} tercile, which is selective of building Mphanda Nkuwa within ≈10 years followed by Devils Gorge and Batoka Gorge toward the end of the horizon; and Cluster A of the top J^{Hyd} tercile, which delays full development by ≈10 years thus taking advantage of discounted capital savings and greater hydropower generation during the later period of higher energy demand.

All clusters in the top J^{Hyd} tercile conflict with environmental performance while favoring moderate irrigation performance. Clusters in the lower and middle J^{Hyd} terciles show greater solution diversity, where some clusters favor environmental performance (Clusters A and B of the lower and middle J^{Hyd} terciles, respectively) while others favor irrigation performance (Clusters B, C, and D, and A, C, and D of the of the lower and middle J^{Hyd} terciles, respectively). Clusters favoring environmental performance tend to build Devils Gorge earliest (Clusters A, B, and D of the lower, middle, and top J^{Hyd} terciles respectively). The best performing irrigation clusters favor building Batoka Gorge and Devils Gorge earlier (Clusters C and D of the middle J^{Hyd} tercile), Mphanda Nkuwa earlier (Cluster C of the lower J^{Hyd} tercile), or building reservoirs late or none at all (Cluster D of the lower J^{Hyd} tercile).

Based on these a-posteriori reservoir sequencing results, stakeholders could select and further investigate sequences which satisfy their objective weights, possibly in connection with a budget limit. However, unlike the tradeoff between hydropower and cost emerging from the predefined reservoir characteristics (e.g., cost, capacity, and location) and optimized operating dynamics (e.g., operational flexibility and system integration), tradeoffs between the hydropower, irrigation, and environmental deficits appear less coherent and perhaps unrelated to reservoir build timing decisions, a supposition we consider in the next section.

4.4. Sensitivity of Infrastructure Pathways to an Extreme Operating Preference

Revisiting the Pareto efficient operating policy sets in Figure 3, we focus attention on the varying environmental and irrigation performance of the best hydropower operating policy across each infrastructure combination (see plot insets for detail). For example, the best hydropower policy for the DG network shows lower environmental and higher irrigation deficits compared to the other reservoir network configurations' best hydropower policy. Conversely, reservoir networks DG-BG, DG-MN, and BG-DG-MN show lower irrigation and higher environmental deficits for their best hydropower operating policies. Differences in the J^{Hyd} objective along the J^{Env}–J^{Irr} tradeoff at the extreme corner of the multi-objective space (<0.01 TWh/yr) may be considered trivial for the hydropower-maximizing stakeholder (see Text S7 in Supporting Information S1 for further discussion of ϵ-dominance). From that perspective, using the extreme single-criteria best hydropower operating policy selection has resulted in unsystematic, or somewhat arbitrary, adoption of a preference along the J^{Env}–J^{Irr} tradeoff for each candidate reservoir network configuration. To demonstrate the effect of this unsystematic policy preference on the results of the sequencing optimization, we perform two additional optimizations with a modified selection of the operating policies tailored either toward environmental or irrigation performance within the top-ϵ-box of J^{Hyd} for each reservoir network configuration.

Figure 6 shows the two Pareto reference sets of the additional sequencing optimizations with objectives plotted relative to the minimum and maximum obtained in the original Best Hydropower operating policy-based sequencing optimization (from Figure 5). As anticipated, the two sets favor either irrigation or environmental performance due to the operating preference systematically adopted for all reservoir network configurations. More importantly, the modified operating policy selection has little effect on the distribution of hydropower performance or NPC as shown by the overlap of performance on those objectives and their containment within the bounds of the original extreme Best Hydropower operating policy-based sequencing. This result emphasizes operating policies' greater effect compared to sequencing decisions on the tradeoffs between environment, irrigation, and hydropower objectives. Stakeholders could more reliably use one of these two sets to retrieve solutions which capture tradeoffs strictly associated with build timing decisions because of their coherence in the operating policy tradeoff preference adopted across all candidate reservoir network configurations.

4.5. Robustness Through a Compromise Operating Policy

We estimate the effects of future hydrologic uncertainty on performance of the efficient reservoir sequencing solutions using a 450-member synthetic streamflow ensemble derived from three regional downscaled climate

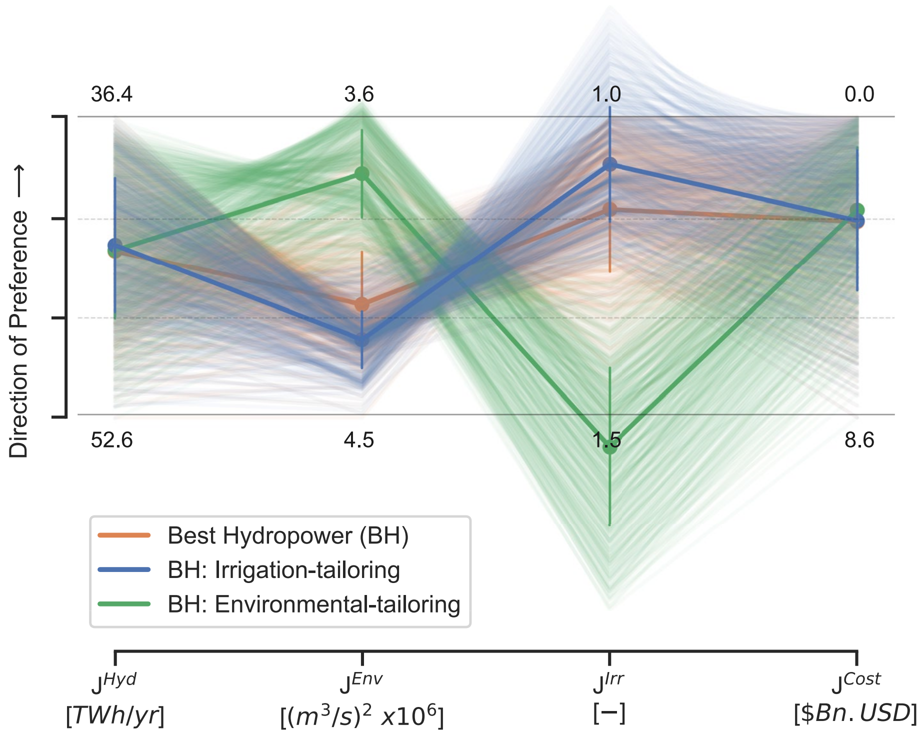

Figure 6. Pareto optimal sets of the two additional sequencing optimizations with tailoring best hydropower operating policy selection toward environment (green) or irrigation (blue) performance. The original sequencing optimization (using the single-best best hydropower policy) is shown in orange. Bold lines with points and bar extensions correspond to the mean plus 1 standard deviation of objective performance across each policy set.

models driven by three representative concentration pathways (see Text S6 in Supporting Information S1). In addition, to assess the effect of changing operating preferences, we re-evaluate sequencing solutions under compromise operating policies (see Figure 3). Figure 7 shows results of the re-evaluation of two selected sequencing solutions: the best hydropower pathway, which builds all three planned dams immediately (within the top J^{Hyd} tercile Cluster B in Figure 5), and the compromise pathway, which builds one reservoir early and two others late (within the middle J^{Hyd} tercile Cluster A in Figure 5).

When re-evaluated with a compromise operating policy, both sequencing solutions show substantial improvements on environmental (50%) and irrigation (80%) objectives with smaller losses in hydropower production (8%) (pink vs. black lines). However, the same cannot be said of seeking compromise with sequencing decisions alone, which attains a 6% and 9% improvement on environment and irrigation deficits, respectively, for a larger 22% loss in hydropower production (solid vs. dashed black line). Furthermore, the compromise sequencing solution performs no better than the best hydropower sequencing solution when re-evaluated under the compromise operating policy (a portion of the synthetic ensemble performs better on environment, though to a small degree). Thus, seeking compromise through sequencing alone effectively sharpens the environmental-irrigation-hydropower tradeoff due to poor hydropower performance from delaying reservoir construction.

Notably, the performance envelopes of synthetic hydrology do not overlap for environmental and irrigation objectives under the two alternative operating policies. This suggests that the operating policy is a greater determinant of environmental and irrigation performance than the uncertainty in future hydrologic conditions sampled here. The synthetic hydrology performance envelopes also narrow for the compromise operating policy on environmental and irrigation objectives, thus showing greater robustness to future hydrologic conditions when compromise operations are adopted.

5. Conclusions

Using the transboundary Zambezi Watercourse as a case study where growing demand for water, energy, and food has led to a resurgence in dam planning and construction, we demonstrated a multi-objective framework that

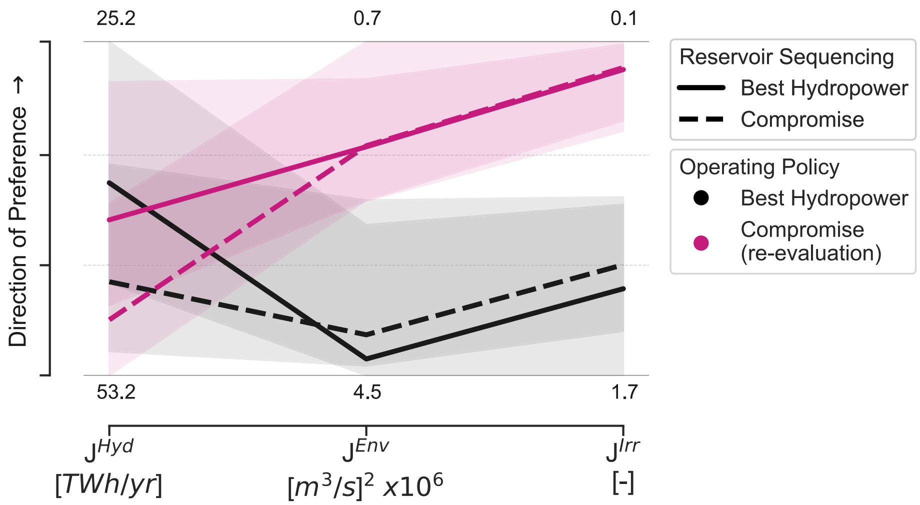

Figure 7. Performance of the best hydropower (solid) and compromise (dashed) reservoir sequencing solutions using the best hydropower operating policy (black) and re-evaluated using the compromise operating policy (pink). Shaded bands show the full range of performance of these solutions re-evaluated under a 450-member synthetic hydrology ensemble.

jointly optimizes sequencing and operations of new multi-purpose reservoirs. Our results, summarized below, strongly indicate that reservoir operating policies are more critical than the selection of dam network configurations and build timings in finding robust solutions for balancing the basin's conflicting human-environmental objectives.

- In exploring Pareto-efficient operating policies for all candidate reservoir network configurations, we found that the shape and magnitude of tradeoffs are shared across all of them, a first indication of operating policies' critical role in determining environmental and irrigation performance relative to hydropower production.
- Only one of the three planned reservoirs was found to amplify the environmental-hydropower tradeoff due to its topographic placement in the system. Sequencing of the planned reservoirs yielded the sharpest tradeoff between hydropower production and the cost of capital, with weaker tradeoffs (relative to operating policy-driven tradeoffs) between hydropower, irrigation, and environmental performance, a second indication of operating policy importance to balancing competing objectives.
- Even during the reservoir sequencing optimization, we found that environmental-irrigation-hydropower tradeoffs were driven by slight preferences embedded in the single-criteria hydropower-maximizing operating policy adopted for a particular candidate reservoir network configuration within the sequence, a third indication of operating policy importance.
- Finally, we found that building all planned reservoirs early (a solution that best minimizes the hydropower deficit) with a compromise-seeking operating policy substantially outperformed delaying reservoir construction to balance the competing human-environmental objectives.

Although the reservoir system, hydrology, planned infrastructure, objective and operating policy formulations, and so forth are exclusive to the particular case study of the Zambezi Watercourse, parallels can be drawn to other large transboundary river basins undergoing a resurgence of dam development and where previous dam construction has already fragmented the basin. In such cases where heavy fragmentation already exists, there is likely one or more existing dams whose operations are the dominant driver of tradeoffs in the basin—like Cahora Bassa in the Zambezi Watercourse. Because of this, the addition of one or more new dams may have little effect on tradeoffs already present in the basin if new coordinated operating polices are jointly considered in their planning. Moreover, delaying their construction effectively surrenders the benefits they would have provided, thus worsening future human-environmental conflicts had they been built and operated in a manner that seeks compromise.

Future extensions to the joint sequencing and operations optimization framework could include dynamically drawing from a broader suite of reservoir operations during the infrastructure sequencing policy search, replacing the adoption of a single-criteria sector preference with transitioning among the entire Pareto efficient management strategies for each possible expansion of the reservoir network. This approach can be expanded to integrate search-based optimization of dam sizing (Bertoni et al., 2019), location (Schmitt et al., 2019), filling strategies

(Zaniolo et al., 2021), and construction lags. Moreover, it could be interesting to explore the potential for dynamically updating operating policies as the future scenario unfolds, which requires specific research into determining when and how to implement such adaptive operations to projected non-stationary hydrologic and socioeconomic trends. Finally, other efforts could be targeted toward integrating recent advances to improve interpretability in direct policy search (Herman et al., 2020) for broader policy relevance when defining short-term operations coupled with long-term expansion strategies.

Additionally, there are a number of uncertainties to be refined in the Zambezi Watercourse in particular. First, while we have explored uncertainty in future hydrology with the available data, expanding the analysis to cover a broader sampling of future conditions including Coupled Model Intercomparison Project Phase 6 scenarios (O'Neill et al., 2016) and stochastic weather (Peleg et al., 2020) and streamflow (Kirsch & Zeff, 2013) generation is crucial for characterizing the Watercourse's vulnerabilities and identifying robust management strategies (likely found in alternative operating policies). Other sources of uncertainties lie within the assumptions of population growth rates and economic indicators from which energy demands are derived as well as several uncertain variables that drive projected irrigation demands such as land cover, yields and irrigation efficiencies (Giuliani et al., 2022).

This study advanced a multi-objective optimization framework for dam planning and management that integrates sequencing of new reservoirs together with their operations. We applied the framework to paradigmatic case of a previously fragmented river basin shared by multiple countries undergoing rapid population and economic growth and a resurgence of dam construction. In such regions, our approach demonstrates the importance of fully integrating operations into dam planning when attempting to balance multiple competing objectives for water resource development.

Data Availability Statement

The code of the HBV models is available in the open-source repository https://doi.org/10.5281/zenodo.5726941. The Zambezi River Basin reservoir operations simulation model contains sensitive hydrologic data, along with hydropower plant characteristics from the Zambezi River Authority (ZRA), Zambia Electricity Supply Corporation (ZESCO) and Hidroeléctrica de Cahora Bassa (HCB), thus it cannot be made public.
The historical hydrologic data on the Zambezi River basin are from the Zambezi River Authority (ZRA) and were collected during the DAFNE project (http://dafne-project.eu/). They are protected by a nondisclosure agreement with ZRA. However, the climate model data used for the temperature and precipitation projections are freely available at the following website: http://www.csag.uct.ac.za/cordex-africa/.

Acknowledgments
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