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Abstract

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Dam reoperation to mitigate changing climate extremes in the Omo River valley

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ABSTRACT

Climate change is projected to increase the intensity and frequency of extremes in river basins around the world. Water infrastructure such as reservoirs are often used to buffer against these extremes, enabling more reliable water supply for human uses like irrigation. Yet this can have negative impacts on the system's ecological flows. In designing water infrastructure for human adaptation to climate change, it is important to consider whether the infrastructure is mitigating or exacerbating climate change impacts on ecological systems. Prior work has found that dams mitigate long-duration extremes but exacerbate short-duration extremes. In this study, we investigate whether reservoir operations can be designed to also yield beneficial climate adaptation outcomes for short-duration high and low flow extremes while still improving average socioeconomic and ecological objectives compared to uncontrolled conditions. We explore this research question

in the Omo River Basin in Ethiopia, where controversy surrounding socio-ecological impacts of recent and ongoing dam construction make this a pressing issue to understand. Using multi-objective optimization of reservoir control rules, we are able to find several policies that can in fact mitigate the impact of climate change on annual maxima and annual 7-day minima. While we do see tradeoffs across reservoir operating policies that best preserve the distribution of these two statistics, we also find compromise policies that mitigate both of these extremes compared to uncontrolled conditions. This shows promise for the role dams can play in climate adaptation to short-duration flow extremes, if their operations are designed with multiple objectives in mind.

INTRODUCTION

Climate change is expected to intensify the hydrologic cycle, and such behavior is already being observed in river basins around the world (Ficklin et al. 2022; Markonis et al. 2019; Huntington 2006). Changes in precipitation patterns, soil moisture content and runoff, and increasing frequency and intensity of extreme rainfall events are causing more extreme floods and droughts (Boulange et al. 2021; Bates et al. 2008). Water resources managers have often relied on reservoirs to mitigate these conflicting risks while still meeting other economic, agricultural, social, and ecological river basin demands (Hall et al. 2014). Consequently, climate adaptation research has largely focused on mitigating impacts by increasing infrastructure development, such as building new dams, restoring or increasing the size of old dams, or transferring water between catchments to balance supplies during drought (Watts et al. 2011; Poff et al. 2016; Zeff et al. 2016).

However, dam planning, construction, and maintenance are all expensive and time-intensive, often costing billions of dollars over many years to complete. For this reason, the economic benefits associated with dams have historically been the primary drivers in decisions about how and when water is released from reservoirs to make up for their large capital costs (Hurford and Harou 2014; Ho et al. 2017). Yet maximizing the economic benefits of water releases from reservoirs disrupts natural flow regimes, which can fragment free-flowing rivers (Graf 2001), severely alter or destroy aquatic ecosystems (Liermann et al. 2012; Poff and Hart 2002; Goodland 2010), restrict access to water resources, cause transboundary conflicts (Zarfl et al. 2015), and hamper water quality (Gyasi et al. 2018). Most concerningly, dams may displace communities, making them both socially and politically controversial (Ehsani et al. 2017; IUCN Water 2019). To date, dam construction has displaced 40-80 million people worldwide, disproportionately affecting indigenous populations (Goodland 2010; Babbitt 2002).

Given these concerns, recent research has focused on integrating social and environmental objectives into siting, sizing and operating dams (Arnold et al. 2023; Watts et al. 2011; Olden et al. 2014; Zarfl et al. 2015; Sabo et al. 2017; Schmitt et al. 2018; Wild et al. 2019; Flecker et al. 2022; Hatchard et al. 2023). However, it is not clear that these designs will still be sufficient under climate change. Altered precipitation patterns could reduce river flows, decreasing the projected economic benefits from hydropower production, stranding over-designed assets at the expense of displaced communities and the ecology (Cole et al. 2014). On the flip side, under-designed infrastructure could lead to increased risks of floods or droughts (Lumbroso et al. 2015). Climate change impacts on flow patterns as well as increased instances of floods and droughts will be felt in absence of infrastructure development as well, though. The interaction between dam operations and climate on downstream flow alteration is complex. Some studies have found that dams mitigate the effects of climate change (Yun et al. 2020; van Oorschot et al. 2018; Giuliani et al. 2016a; Mueller 2007) while others have found that climate change impacts exceed the impacts of dams and other human interventions (Ficklin et al. 2018), or that dams exacerbate climate change impacts (Mittal et al. 2016). Chalise et al. (2021) found that the combined influence of dams and climate trends can either enhance or diminish overall alteration at a local level, deviating what would be predicted based on their isolated effects: dams may intensify, ameliorate, or produce dual effects on flow alterations driven by hydroclimate depending on the observed climate trends, dam size, and dam purpose(s). Of note, they found that dams generally mitigate the impacts of climate change on long-duration extremes (30-90 day high or low flows) but exacerbate their impacts on short-duration extremes (1-7 day high or low flows). This begs the question: "Can alternative operations be discovered that also mitigate the impacts of climate change on these short-duration extremes, while still improving expected socioeconomic and ecological performance compared to uncontrolled conditions?"

In this study, we investigate whether closed loop operating policies can do just that: reduce socio-ecological tradeoffs while also mitigating the impacts of climate change on short-duration high and low flow extremes. We explore this question in the Omo River Basin of Ethiopia (Figure 1), a basin grappling with these economic development and climate change adaptation challenges (Zaniolo et al. 2021b; Jordan et al. 2022). Over the past two decades, three hydro-electric facilities have been constructed along the Omo River (Gilgel Gibe I, II, and III), with a fourth power plant under construction (Koysha). At the time of its construction, Gibe III increased Ethiopia's installed hydroelectric capacity by 80%, and, upon completion, the Koysha dam will be the second largest dam in the country, after the Grand Ethiopia Renaissance Dam. With a combined capacity of 4,634 MW and 21,202 Mm^3 of reservoir storage, these dams can help promote economic growth in the region by offering stable hydropower generation and a reliable water supply for irrigation of new large-scale private sugarcane and cotton plantations (Woodroofe 1996; IEA 2016; Asress et al. 2013; Zaniolo et al. 2021a; Sundin 2017; Avery 2012; Davidson 2015; Hodbod et al. 2019; Oakland Institute 2011; Human Rights Watch 2017). However, the dams have also altered the historical flow pattern influenced by monsoonal rains, posing risks to the indigenous communities practicing recession agriculture, and ecosystems in the Lower Omo Basin and Lake Turkana at its mouth (Hathaway 2009; Abbink 2012; Fratkin 2014; Carr 2017; Johnston 2009).

In prior work, we designed reservoir operating policies in the Omo River Basin to balance competing economic and socio-ecological objectives, and then assessed how robust performance on these objectives was to possible climate futures (Giuliani et al. 2022; Jordan et al. 2022). However, all of these objectives focused on mean performance, when the greatest concerns about climate change are its impacts on extremes. In Jordan et al. (2022), we constrained operations not to exceed historical maximum flows and to meet minimum environmental flow thresholds downstream of the dams when simulated over the historical record. Yet changing climatic stressors may force these conditions to be violated, which could create a new set of challenges in the basin. Here we perform a climate risk assessment to determine whether our optimized operating policies can also mitigate the impacts of climate change on short-duration high and low flow statistics. While the findings of this study are specific to the Omo River Basin, the work illustrates a framework that can be applied to other locations to both design reservoir operations to manage conflicting objectives, and to assess the applied research question of whether reservoirs can mitigate the impacts of climate change on short-duration high and low flow extremes.

METHODS

To answer this study's research question on whether water infrastructure can mitigate climate change impacts on short-duration high and low flow extremes, we utilize the Multi-Objective Robust Decision Making (MORDM) framework (Kasprzyk et al. 2013). MORDM is one of several robustness analysis methods used to find water management strategies for balancing conflicting objectives under uncertainty. In this study, we use MORDM in a new way to investigate whether reservoir operations mitigate or exacerbate climate change impacts, determined by whether they are more or less robust the projected uncontrolled conditions in reproducing distributions of high and low flows extremes experienced under historical uncontrolled conditions. Following the robustness taxonomy of Herman et al. (2015), our application of MORDM first defines alternative reservoir operating policies to evaluate using multi-objective optimization. Second, the performance of these policies is evaluated under different states of the world defined by climate projections from the Coupled Model Intercomparison Project 5 (CMIP5). While there may be other uncertainties that could influence performance beyond climate change, such as population growth and land use change, we focus our analysis on the specific research question of how climate change impacts the system with and without reservoir infrastructure. Third and finally, we answer our research question by quantifying the robustness of the operating policies using a satisficing metric specifying the percent of the climate projections in which high and low flow extremes are mitigated compared to a no-infrastructure scenario. These three steps of the MORDM process are described below.

Multi-Objective Optimization

This study builds off prior work by Jordan et al. (2022) in which a new reservoir optimization module was incorporated into the Soil and Water Assessment Tool (SWAT), enabling the joint exploration of changing reservoir operations and climate conditions on socio-ecological performance metrics. In the new reservoir optimization module, reservoir operating rules are described by Gaussian radial basis functions (RBFs) that define how much water to release from system reservoirs as a function of different state variables, such as the reservoir storage and day of the year. Mathematically, this can be described by equation 1:

$$u_t^k = a_k + \sum_{i=1}^{N} w_{i,k} \exp\left(\sum_{j=i}^{B} \frac{\left((v_t)_j - c_{i,j}\right)^2}{b_{i,j}^2}\right) \tag{1}$$

where u_t^k is the normalized release from the k-th reservoir at time t, $(v_t)_j$ is the j-th normalized input variable at time t, B is the number of input variables, N is the number of RBFs, and a_k, $w_{i,k}$, $c_{i,j}$ and $b_{i,j}$ are constant parameters to be optimized. In this study, $B = 5$ inputs were used: the volume of the three storage dams at time t (Gibe II does not have storage), and two variables capturing seasonality: $\sin(2\pi t/365)$ and $\cos(2\pi t/365)$. The policies were defined by $N = 9$ RBFs, and $K = 3$ for the releases from the three storage dams. This yielded a total of $K + N(2B + K) = 120$ decision variables.

Jordan et al. (2022) used a simulation-optimization approach called Evolutionary Multi-Objective Direct Policy Search (EMODPS; Giuliani et al. (2016b)) to optimize these 120 parameters. In the simulation phase, the true releases from the reservoirs, r_t^k, are determined by back-transforming the normalized releases and then subjecting them to physical and minimum environmental flow constraints. At the end of the simulation, multiple performance metrics are computed. A multimaster parallelization of the Borg multi-objective evolutionary algorithm (MOEA; Hadka and Reed (2013, Hadka and Reed (2015)) was used to optimize the RBF parameters to improve the performance of these objective functions. This process yields a "Pareto set" of alternative reservoir operating policies, p_θ^*, in which no policy outperforms another on all objectives, but rather requires trading off performance across them. The objectives were to 1) maximize average annual hydropower production (GWh/year), 2) minimize average squared deviations from mean daily flow targets for environmental flows (cms^2/day), 3) minimize average daily squared deviations below flow targets for flood-recession agriculture during the growing season (cms^2/day), and lastly maximize average annual production of 4) sugarcane and 5) cotton in the Omo River Basin (metric tons/year). The optimization problem is described by equations 2-5:

$$p_\theta^* = argmin_{p_\theta}(\bar{J}) \tag{2}$$

$$\theta = [a_k, w_{i,k}, c_{i,j}, b_{i,j}] \tag{3}$$

$$\bar{J} = | - J^{hyd}, J^{env}, J^{rec}, -J^{sug}, -J^{cot} | \tag{4}$$

subject to:

$$\max\left(q_{max}^{LO} - q_{hmax}^{LO}, 0\right) = 0 \tag{5}$$

where J^{hyd}, J^{env}, J^{rec}, J^{sug}, and J^{cot} are the system objectives defined by equations 8-12 in Appendix I. q_{max}^{LO} is the maximum simulated flow in the Lower Omo, which is constrained not to exceed q_{hmax}^{LO}, which equals 3,290 m^3/s, the historical maximum flow simulated by SWAT over the same period (1989-2018) in absence of reservoirs. This constraint was included to ensure that reservoir releases would not inundate the Lower Omo Valley. All objectives and constraints were developed through a participatory process with stakeholders in the basin through "Negotiation Simulation Labs" held as part of the DAFNE project (Giuliani et al. 2022).

Jordan et al. (2022) showed that the Pareto-optimal reservoir operations defined by these RBFs were better able to compromise across system objectives than operations designed using prior SWAT operating rule forms. Furthermore, many of these policies enabled better performance across all objectives than if there were no reservoirs, both under historical and projected future climate conditions.

Limitations of Optimization Objectives

While the operation objectives defined in the preceding section serve as mathematical representations of conflicting stakeholder needs in our optimization framework, it is important to acknowledge the potential distinctions between these mathematical framings and the nuanced realworld operating objectives of hydropower facilities. For example, the hydropower objective seeks to maximize average annual hydropower output, but does not respond to changes in seasonal or inter-annual demand. However, in absence of information on electricity market prices, maximizing hydropower production is a close proxy, and in alignment with Ethiopia's goal of becoming an energy exporter. With respect to environmental flows and recession agriculture, these objectives are both designed to re-create natural flow patterns in the Omo River basin, enabling the design of operating policies that mimic the cyclo-stationary hydrograph. However, these objectives do not capture year-to-year variability that can benefit many ecosystems (Whipple and Viers 2019). While there could be alternative mathematical formulations that better capture stakeholders' objectives, our process of identifying alternative operations and assessing their ability to mitigate climate change impacts on different operating objectives can easily be applied to alternative mathematical formulations of these operating goals.

Definition of States of the World

Whether reservoir operations mitigate or exacerbate the impacts of climate change is likely to depend highly on the distribution of future stochastic inflows. Operations may mitigate impacts in some potential futures and exacerbate them in others. We seek to identify if operating policies can more closely reproduce historical uncontrolled conditions across more possible distributions of future stochastic inflows than projected uncontrolled conditions. To identify "possible distributions of future stochastic inflows" we define different possible future "states of the world" from downscaled CMIP5 climate projections. The goal is to see if the operating policies identified by Jordan et al. (2022) not only reduce the mean socio-ecological tradeoffs of reservoir development, but also provide adaptation strategies that mitigate impacts of climate change on extreme short-duration flood and drought conditions across more possible futures. We use the same 48 downscaled climate projections described in Jordan et al. (2022). The reader is directed to that study for more details on the downscaling method. The 48 downscaled projections consist of 17 general circulation models (GCMs) run under different representative concentration pathways (RCPs) ranging from 2.6-8.5. The models and scenarios are listed in Appendix II Table 1.

Of course, alternative scenarios could be used for robustness analysis, such as CMIP6 projections rather than CMIP5, and the true future may lie beyond the uncertainty of either of these projections. Prior studies have shown that alternative ensembles may result in different policy rankings on robustness metrics (Reis and Shortridge 2020; McPhail et al. 2020; Quinn et al. 2020; Bonham et al. 2024). However, ranking inconsistencies occur within a neighborhood of similarly ranked policies; globally rankings are quite consistent. Consequently, if *several* policies are more robust than historical uncontrolled conditions, this should hold for at least some of those policies under alternative ensembles, and we can be confident that optimized operations can mitigate impacts of climate change.

Robustness Calculation

Definition of Wet and Dry Extremes and Operational Robustness

To discern whether optimized reservoir operating policies mitigate or exacerbate short-duration wet and dry hydrological extremes, we first define metrics quantifying these conditions. To capture extreme wet and dry conditions, we select two of the 33 indicators of hydrological alteration defined by Gao et al. (2009), with a focus on short-duration extreme flow statistics: the annual maximum daily flow and the minimum 7-day average flow. We denote the time series of annual maximum daily flows in the Omo River delta the annual maxima series (AMS). Annual maxima series are used in flood frequency analysis to aid flood management, reservoir planning, and irrigation scheduling (Tiwari et al. 2017).

We denote the time series of annual minimum seven-day flow series as 7QS. This flow indicator captures both persistence (seven-day average) and severity (minimum). Average flows over shorter or longer windows can alternatively be used to capture more intense or persistent ecological drought impacts. Our environmental flows objective should capture impacts on long-duration low flows, and prior work by Chalise et al. (2021) found dams tend to mitigate climate change impacts on these statistics. We seek to discover if operations can mitigate shorter-duration extremes. Our minimum environmental flow constraint on the reservoir releases should reduce the intensity one-day low flows, but we have no explicit mechanism in our optimization to control seven-day low flows. As such, we choose this duration for our analysis as a robustness check on our optimized reservoir operating policies. Seven-day low flows are also used frequently to define environmental droughts such as the most commonly used low flow index in the United States: the seven-day, ten-year low flow, or 7Q10, defined as the annual minimum seven-day low flow that occurs, on average, once every ten years (Riggs 1980).

Gao et al. (2009) use flow indicators like annual seven-day minima to calculate indices of hydrological alteration, quantified as the integrated difference between the distribution of these variables before and after infrastructure development. Following Kroll et al. (2015), we instead perform hypotheses tests to see whether the altered distribution is statistically different from the natural distribution. To do this, we calculate AMS and 7QS time series in the Omo River delta from SWAT simulations under a historical uncontrolled scenario (HUC) from 1989-2018, as well as projected uncontrolled scenarios (PUC) from 48 downscaled climate scenarios at mid-century (2040-2069). This allows us to assess how ecological low flow and flood risks might change in the future without reservoir infrastructure, i.e. in absence of adaptation. We repeat this process using each of the optimized reservoir release policies from Jordan et al. (2022) to see if these operating rules exacerbate or mitigate these changing vulnerabilities. We then compute the "robustness" of each operating policy and PUC using a satisficing metric quantified as the percent of climate projections in which some minimum performance threshold is met (Starr 1963; Schneller and Sphicas 1983). Here we define three minimum performance thresholds: no statistically significant difference in the distribution of 1) 7QS, 2) AMS, or 3) Both 7QS and AMS compared to HUC. Operating policies with a higher satisficing metric than PUC tend to mitigate the impacts of climate change on extremes, whereas operating policies with a lower satisficing metric tend to exacerbate the effects of climate change. We define the policy that performs best on each of these metrics as the Low Flows, High Flows, and Compromise policies, respectively.

Statistical Analyses

Following Kroll et al. (2015), we compare the distributions of historical and future AMS and 7QS time series using the two-sample Kolmogorov-Smirnov (K-S) test to help identify which policies are mitigating or exacerbating the effects of climate change on extreme high and low flows. For each of the Pareto-optimal operating policies discovered from the optimization and the projected uncontrolled scenario, we use the K-S test to see if the distributions of the AMS and 7QS in each of the climate projections are statistically different from the historical uncontrolled scenario (1989-2018) at mid-century (2040-2069). Based on the K-S test results, we then calculate the percent of projections in which each policy's distributions of high and low flows do *not* have a statistically significant difference from the historical uncontrolled scenario ($p > 0.05$). Reservoir operating policies that are not statistically different from HUC in a greater percentage of projections than PUC mitigate the impacts of climate change on low flows.

In each projection, we also test whether or not there is a monotonic trend in the 7QS and AMS time series for each policy and the uncontrolled scenario. Operating policies that reduce the number of projections in which these time series exhibit a monotonic trend compared to the projected uncontrolled scenario provide favorable climate adaptation. We use the non-parametric Mann-Kendall trend test for this analysis (Mann 1945; Kendall 1948). The Mann-Kendall trend test is used to test if there is a monotonic trend by comparing each value in a time series with all future values and tracking the number of increases, decreases, and ties across all timesteps. The test statistic, Z, is then computed from S, the difference between the number of positive changes and the number of negative changes across all timesteps, and V, its variance:

$$Z = \begin{cases} \frac{S-1}{\sqrt{v}} & \text{if} S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{v}} & \text{if} S < 0 \end{cases} \tag{6}$$

$$V = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{7}$$

where n is the number of time steps, t_i is the number of ties and i is the extent of the tie. Z is normally-distributed, so if $Z < 1.96$ there is a statistically significant decreasing trend, while if

$Z > 1.96$, there is a statistically significant increasing trend ($\alpha = 0.05$).

RESULTS AND DISCUSSION

The results of our analysis are organized as follows. First, we illustrate the ability of the reservoir operating policies to balance socio-ecological tradeoffs over the historical record compared to uncontrolled conditions. Next, we assess their ability to mitigate changing high and low flow extremes with respect to preserving their distribution and reducing their trends. Finally, we investigate their ability to reproduce historical seasonality into the future, and to better balance socio-ecological objectives than without infrastructure.

Ability of reservoir operations to balance socio-ecological tradeoffs over the historical record

First we investigate how well alternative reservoir operations can balance conflicting socio-ecological objectives in the Omo River Basin compared to historical uncontrolled conditions (HUC). The historical performance of optimized reservoir operating policies is plotted on a parallel axis plot in Figure 2, in which each colored line represents a different operating policy that crosses each axis at its performance on that axis's objective, where the favorable direction on each axis is down. The color of each line represents that policy's performance on the environment objective, with green policies performing the best and red policies performing the worst. Recall that the environment objective is to minimize squared deviations from a cyclostationary mean daily flow sequence, so policies that consistently follow that pattern each year are favored.

For reference, the performance of HUC on all objectives is shown by a black dashed line. From Figure 2a, we see that many of the policies in red do well on sugar and cotton production at the expense of performing worse than HUC on meeting the environment objective, illustrating a tradeoff in performance. However, there are also many policies that are able to outperform HUC on all objectives. Figure 2b has made all these policies opaque, while those that are outperformed by HUC on at least one objective are transparent. Fortunately, about half of the policies remain opaque, meaning they are able to outperform HUC on all objectives over historical conditions.

While it is expected that reservoir operations would enable improved hydropower, sugar cane, and cotton production, it is counter-intuitive that they could improve environmental flows. We find this because the environment objective rewards replication of cyclostationary conditions without year-to-year variability. While the objective is designed to ensure operational strategies recreate naturally-occurring seasonality of high and low flows in the Omo River basin, we recognize that some interannual variability is beneficial to many ecosystems (Whipple and Viers 2019). When certain policies perform "better" than the uncontrolled scenario on this objective, it means that these policies are more commonly replicating the cyclostationary mean flows than was possible without reservoir operations, and not necessarily that the Lower Omo and Lake Turkana are in a better ecological condition than they were prior to dam construction.

Ability of reservoir operations to mitigate changing climate extremes

While Figure 2b shows that several reservoir operating policies can outperform HUC on all objectives over the historical record, this may change in the future, as climate change is expected to increase extreme wet and dry flow conditions. Here we investigate whether reservoir operations can mitigate those changes compared to projected uncontrolled conditions.

Identification of robust operating policies

Figure 3a-c shows the satisficing metric of all operating policies at mid-century on (a) low flows, (b) high flows, and (c) both low and high flows by an orange line. Policies are sorted within each panel from those with the highest satisficing metric to the lowest. A black line also indicates the satisficing metric under PUC, while the best policy on each metric is indicated by orange, blue, and white vertical lines for low flows, high flows, and both low and high flows, respectively. We refer to these policies as the "Best Low Flow Policy", "Best High Flow Policy", and "Best Compromise Policy", respectively, throughout the remainder of the paper. For context, the performance of these three policies on the optimization objectives over the historical record is shown in Figure 3d. Over the historical record, the Best Low Flow Policy outperforms HUC on all objectives, while the Best High Flow Policy does better on all but environmental flows, and the Best Compromise Policy does better on all but cotton production.

In Figure 3a, we can see that there are a few policies that perform better in preserving historical uncontrolled low flows than PUC, suggesting operating policies *can* be designed to mitigate these short-duration low flow extremes. Yet most policies dampen short-duration low flows, as found in Chalise et al. (2021). However, Figure 3b shows that many policies preserve pre-dam high flow extremes better than the uncontrolled scenario, contrary to their findings. We will explore if this might be from reservoirs dampening increasingly high extreme flows in wet projections, reservoirs supplementing decreased high flows in particularly dry projections, or a combination of the two. Finally, the Best Compromise Policy preserves pre-dam high *and* low flows in only about 37% of climate projections considered, highlighting the trade-off in mitigating these two different types of water resources extremes (Figure 3c). However, while this is low, it is even lower for PUC. In fact, several policies maintain pre-dam extreme distributions of both high and low flows in more projections than PUC. Note, that does not mean these policies preserve extreme high flows in more projections than PUC *and* they preserve extreme low flows in more projections than PUC; rather it means that for these policies, there are more projections in which *both* of these distributions are preserved simultaneously than for PUC. The fact that so many policies outperform PUC on both 1) the high flows and 2) high and low flows satisficing measures suggests that even if a broader ensemble of climate uncertainty were used, or alternative projections such as CMIP6, there would be some optimized policies that can outperform HUC on these metrics.

Comparing the best policies on these different robustness metrics, we see clear trade-offs; the Best High Flow Policy is the worst of the three policies in preserving historical low flows, and the Best Low Flow Policy is the worst of the three policies in preserving historical high flows. The Best Compromise Policy, which best preserves both high and low flows, strikes a better balance in managing these extremes; it performs just about as well as the projected uncontrolled scenario in preserving low flow extremes (Figure 3a), while outperforming the projected uncontrolled scenario in preserving high flows (Figure 3b) and both high and low flow extremes together (Figure 3c).

Interestingly, while these policies have evident tradeoffs between high and low flow robustness, both the low flow and compromise policy perform similarly (and quite well) on the environmental flows objective historically (Figure 3a). This highlights the importance of considering multiple ecological performance objectives, as policies that perform similarly on reproducing mean flows and seasonality targeted by the environmental flows objective (see equation 9) may not be reproducing extremes in the same way.

Throughout the rest of the paper, we will explore the Best High Flow Policy, the Best Low Flow Policy, and the Best Compromise Policy in more detail. However, there are a number of policies that outperform the projected uncontrolled scenario across climate projections at mitigating low flows, high flows, or both while tracing different trade-offs in the objective space. The policies explored in the paper therefore represent just one pathway for mitigating extreme flows, achieved through a specific set of trade-offs between the optimization objectives considered in this study.

Evaluation of extremes distributions for select policies

We visualize the distributions of short-duration high and low flows from the four robust operating policies and the projected uncontrolled conditions using a plot of their empirical cumulative distribution functions (ECDFs; Figure 4). Each line represents a separate climate projection, colored by the average flow in the Omo Delta in that projection's uncontrolled scenario as a proxy for how wet or dry that climate projection is. The distribution under historical uncontrolled conditions is shown in black. Projections in which the 7QS and AMS distributions do not statistically significantly differ from the historical uncontrolled scenario are bold and opaque, while those that are statistically significantly different are thin and transparent. Which projections have no statistical difference in the ECDF from HUC is also shown in the binary color bar at the right of each figure. In each color bar, the climate projections have been sorted from wet at the top to dry at the bottom and colored black if the distribution is not statistically different than HUC, and white otherwise.

Projections produce a wider spread in extreme short-duration low and high flows compared to the historical uncontrolled scenario. This is unsurprising, as climate change is projected to cause both more severe droughts and more intense flooding (Trenberth 2011; Boulange et al. 2021; Bates et al. 2008). The projected uncontrolled scenario preserves historical seven-day low-flows fairly well, except for in the driest future conditions (Figure 4a). However, uncontrolled scenarios only preserve the distribution of annual maxima in very dry projections, which suggests that there is an increased flood risk in most projections (Figure 4b). The best policy for preserving low flow distributions is able to preserve the distribution of low flows in many projections that are both wet and dry (Figure 4c), but only preserves the distribution of high flows in a few moderately wet climate projections (Figure 4d). While this suggests that this policy may dampen high flows in dry projections, its performance on the recession agriculture objective almost always outperforms the projected uncontrolled scenario across projections (see Figure 7). However, it fails to mitigate the most extreme flood events, where flows reach nearly 10,000 cms, which would be a devastating flood for indigenous populations in the Lower Omo Valley.

The best policy for preserving high flow distributions mirrors the historical uncontrolled high flow distribution in most projections (Figure 4f). However, this policy completely alters the distribution of low flows across all climate projections, severely reducing seven-day low flows in all but a few extremely wet projections (Figure 4e). This would have a devastating effect on indigenous people and ecological health in the Lower Omo Valley. Future work should explore if reduced irrigation abstractions could improve socio-ecological outcomes from this policy without sacrificing a large portion of annual yields.

While very wet conditions are needed for the Best Low Flow Policy to preserve HUC's high flow distributions, and for the Best High Flow Policy to preserve HUC's low flow distributions, the Best Compromise Policy is able to preserve the distribution of both high and low flows fairly well across almost all projections (Figures 4g and 4h). This highlights the value of multi-objective optimization in not only identifying solutions that can compromise across conflicting objectives, but also adapt to a range of climate conditions, continuing to balance competing concerns.

Trend identification in extremes for select policies

We next identify trends in short-duration high and low flows from historical observations to the end of mid-century for the projected uncontrolled scenario and the three robust policies using the Mann-Kendall trend test. We summarize the results in Figure 5, where we show the percent of projections with no trend from historical in gray, with an increasing trend in blue, and a decreasing trend in orange.

In absence of water infrastructure development (the projected uncontrolled scenario), the seven-day low flows show no trend in 50% of the climate projections, an increasing trend in 25% of projections, and a decreasing trend in 25% of projections. The Best Low Flow Policy and the Best Compromise Policy both increase the share of projections in which there is no trend in low flows while decreasing the share of projections in which low flow extremes increase. This indicates the reservoirs are able to replenish otherwise decreasing flows in several climate projections, enabling favorable adaptation. The best policy for preserving high flow distributions, however, drastically increases the share of projections with a decreasing trend in low flows, indicating unfavorable adaptation.

With respect to high flows, the projected uncontrolled scenario most commonly shows a statistically significant increasing trend of the annual maxima series from the historical time period to mid-century, which highlights an increased flood risk to downstream communities under climate change in absence of infrastructure development (Figure 5b). This could have negative implications for recession agriculture as well. The robust policies considered here clearly help mitigate that risk, increasing the share of projections under which there is no trend or a decreasing trend in the annual maxima series. Once again, the compromise policy appears to be a favorable solution, yielding no meaningful change in the number of projections with low flow trends while decreasing the number of projections with increasing high flow trends.

Ability of reservoir operations to reproduce historical seasonality and socio-ecological objectives

Figure 3 showed that reservoir operations can mitigate changes in extreme short-duration high and low flows that would otherwise be projected under uncontrolled conditions. Yet it is important to reproduce mean performance as well, particularly for standard operating objectives. Here we investigate how typical flow conditions and operating objectives are projected to change when using different operating rules compared to uncontrolled conditions.

For each robust policy, we use simulated flows in the Omo River delta across projections to estimate the relative frequency of observing different flow magnitudes downstream of the dams over the course of the year. Figure 6 shows the percent of simulated years in which the flow was at different magnitudes each calendar day, with high frequencies shaded red, moderate frequencies yellow, and low frequencies blue. The solid black lines show the historical daily high and low flow magnitudes for each day of the year and the dashed black line shows the historical daily median. While certain projections produced flows higher than 4,000 cms, we bound the plot to this range for visualization purposes because flow events greater than 4,000 cms are so rare that they are difficult to see on the plot and we already explored how the distribution of extremes changed above.

Across policies, the shape of the frequency distributions is similar over time, with flows of the highest frequency in red rising in July for the rainy season and decreasing again in late October, generally mirroring the historical median. However, there are some key differences. The Low Flow and Compromise policies most frequently keep flows at or slightly above the historical median during the dry period from January to March (Figures 6b and 6c). They are also able to reduce the amount by which the lowest flows during the wet season fall below the historical low during this period compared to PUC. Similarly, they are able to reduce the frequency of exceedances of the historical maxima throughout the year compared to PUC.

The best policy for preserving high flows most effectively reduces the frequency of flows above the historical maximum compared to PUC; however, it does this by completely altering the seasonality of flows in the Omo River, drawing out the wet season flows so that the peak occurs later than historically (Figure 6d). In prior work, we found such behavior to be favorable for cotton production (Jordan et al. 2022), which this policy heavily favors. However, while the changed seasonality for cotton production has the unintended benefit of reducing high flows, it comes at the expense of preserving mean annual environmental flows. This policy also creates a rise in flows between April and May that did not exist under historical uncontrolled conditions. Low flows during this period are critical for creating fish spawning habitat and for exposing fertile ground for planting ahead of the flood season for flood recession agriculture, so this change to the natural flow pattern could have negative ecological and agricultural outcomes. Following this artificial peak, the Best High Flow Policy then tends to dampen flows in the Omo River downstream of the dam, as shown by the high frequency of observing flows much lower than historical minima from late

May to the end of August, again causing detrimental environmental flow conditions.

The behavior of the Best High Flow Policy in Figure 6 highlights potential drawbacks of seeking to only mitigate one extreme; however the behavior of the Best Low Flow and Best Compromise Policies highlights the power of multi-objective policy design in discovering favorable climate adaptation strategies. The ability of these policies to reproduce the natural flow pattern under climate change suggests these solutions outperform PUC on the environmental flows objective. This is confirmed in Figure 7, which shows the performance of the three robust policies and PUC on each of the operating objectives in each of the climate projections. Each line in this figure represents a different policy, with its performance on the five objectives plotted as a function of the mean annual flow or temperature in the climate projections. The favorable direction in each panel is down. The climate projections are sorted from low to high flows for the hydropower, environmental flows, and recession agriculture objectives, while they are sorted from low to high temperatures for the sugar cane and cotton production objectives, as these are the most predictive variables of performance.

Across panels, it can be seen that all three robust policies are almost always below PUC, indicating they are performing better on nearly every objective in nearly every projection. As such, the near-natural flow conditions of the low flow and compromise policy shown in Figure 6 also enables continued recession agriculture downstream. Furthermore, this is achieved despite also drawing irrigation water for increased sugar and cotton production, and while producing a clean source of power. This illustrates how well-designed multi-objective reservoir operations can facilitate beneficial climate adaptation outcomes.

CONCLUSIONS

This study evaluates the robustness of closed-loop, nonlinear reservoir operating policies in mitigating the impact of climate change on short-duration low and high flow statistics in the Omo River basin. We find that tradeoffs emerge in mitigating the impacts of climate change on these opposing flow extremes, as policies that best mitigate annual do poorly in reproducing annual seven-day minima and vice versa. We also find that many policies replicate historical mean flows, but do not necessarily reproduce extremes in the same way. This underlines the importance of exploring policy performance beyond historically defined objectives when considering climate change, a lesson that should be applied to other basins as well, as policies that performed similarly on our environmental flows objective in the Omo River Basin had significantly different outcomes for high and low flow extreme events across climate change projections.

However, we also demonstrate that water infrastructure development can improve climate resilience, as we were able to identify compromise reservoir operating policies that produce more balanced socio-ecological outcomes while mitigating the impacts of climate change on short-duration high and low flow extremes. This highlights the value of multi-objective optimization in producing a set of alternative operations to choose from, and in performing climate stress tests to inform that selection, another recommendation applicable to other basins. Here, we were able to find a compromise solution that mitigated the impacts of changing short-duration high and lows flows compared to a projected uncontrolled scenario at mid-century while also improving other system objectives. Many policies actually had worse robustness metrics than the projected uncontrolled scenario, and simpler design procedures may have only discovered these policies. Future work incorporating forecasts into the policy design could further improve performance in the compromise region, as season-ahead forecasts could be used to adapt reservoir storage levels up or down in a way that mitigates increasing high flows or decreasing low flows while maintaining favorable socio-ecological outcomes.

APPENDIX I. OBJECTIVE FUNCTIONS

The first optimization objective was to maximize the average annual hydropower production across all reservoirs and time steps, J^{hyd}:

$$J^{hyd} = \frac{1}{A} \sum_{t=0}^{T-1} \sum_{k=1}^{K+1} \eta_k \rho g h_t^k min(r_t^k, rMax^k) \tag{8}$$

where η_k is the efficiency of reservoir k, ρ is the density of water, g is the gravitational constant, h_t^k is the head at reservoir k on day t, r_t^k is the release from reservoir k at time t $rMax^k$ is the turbine capacity of reservoir k, and A is 30 years. Hydropower production is summed over $K + 1$ reservoirs for the three storage dams plus Gibe III over the entire time horizon of $T = 10,957$ days (30 years from 1989-2018).

The second objective is an environmental flows objectives, J^{env}, to minimize the sum of squared deviations of simulated flows in the Omo River delta on day $t+1$, q_{t+1}^{delta}, from natural flows simulated by the SWAT model on that calendar day in absence of reservoir infrastructure, $q_{(t+1)\%365}^{natOmo}$, across all T time steps:

$$J^{env} = \frac{1}{T} \sum_{t=0}^{T-1} \left(q_{(t+1)\%365}^{natOmo} - q_{t+1}^{delta} \right)^2 \tag{9}$$

The third objective is the recession agriculture objective, defined mathematically, as minimizing the sum of squared deviations of flows in the lower Omo q_{t+1}^{LO} below a target artificial flood flow for that calendar day $q_{(t+1)\%365}^{LO}$:

$$J^{rec} = \frac{1}{T} \sum_{t=0}^{T-1} \left(max\left((q_t^{AF} - q_{(t+1)\%365}^{LO}), 0 \right) \right)^2 \tag{10}$$

The target artificial flow for recession agriculture is 0 cms for most of the year until August 29, when it linearly increases from 240 cms to a peak of 1200 cms on September 2, where it remains until September 11, when it decreases linearly back to 0 cms on September 16.

The final two objectives, J^{sug} and J^{cot}, are to maximize sugar and cotton production, respectively, over $A = 30$ years:

$$J^{sug} = \frac{1}{A}\sum_{a=0}^{A-1}\sum_{s=1}^{S} Y_a^s \tag{11}$$

$$J^{cot} = \frac{1}{A}\sum_{a=0}^{A-1}\sum_{c=1}^{C} Y_a^c. \tag{12}$$

where Y_a^s is the sugar yield in sugar-growing hydrologic response unit (HRU) s in year a, and Y_a^c is the yield of cotton in cotton-growing HRU c in year a.

APPENDIX II. TABLES

Below is the table of CMIP5 climate projections used in this study.

DATA AVAILABILITY STATEMENT

- Some code generated or used during the study are available in a repository online in accordance with funder data retention policies: https://github.com/sjordan29/DamReoperationOmo

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List of Tables

TABLE 1. CMIP5 climate projections used in the study

Model	RCP			
	2.6	*4.5*	*6.0*	*8.5*
ACCESS 1.0	-	✓	-	✓
CCSM4	-	✓	✓	✓
CESM1-BGC	-	✓	-	✓
CMCC-CESM	-	-	-	✓
CMCC-CMS	-	✓	-	✓
CMCC-CM5	✓	✓	-	-
CSIRO-Mk3.6.0	✓	✓	✓	✓
GFDL-CM3	✓	-	✓	✓
GFDL-ESM2G	✓	✓	✓	✓
GFDL-ESM2M	✓	✓	✓	✓
HadGEM2-CC	-	✓	-	✓
HadGEM2-ES	-	-	✓	-
MIROC-ESM-CHEM	✓	✓	✓	✓
MIROC-ESM	✓	✓	✓	✓
MPI-ESM-LR	✓	✓	-	✓
MPI-ESM-MR	✓	✓	-	✓
NorESM-M	✓	✓	✓	✓

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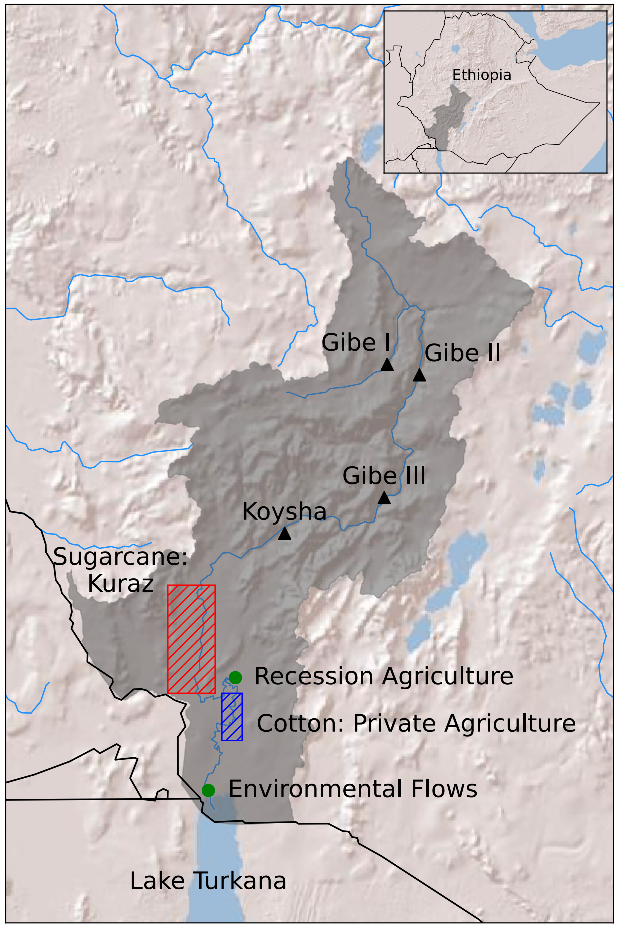

Fig. 1. Map of the Omo River Basin and its hydroelectic dams (existing and under construction), as well as the different stakeholders they serve: private sugarcane and cotton agriculture, indigenous recession agriculture, and environmental flows. Figure adapted from Jordan et al. (2022).

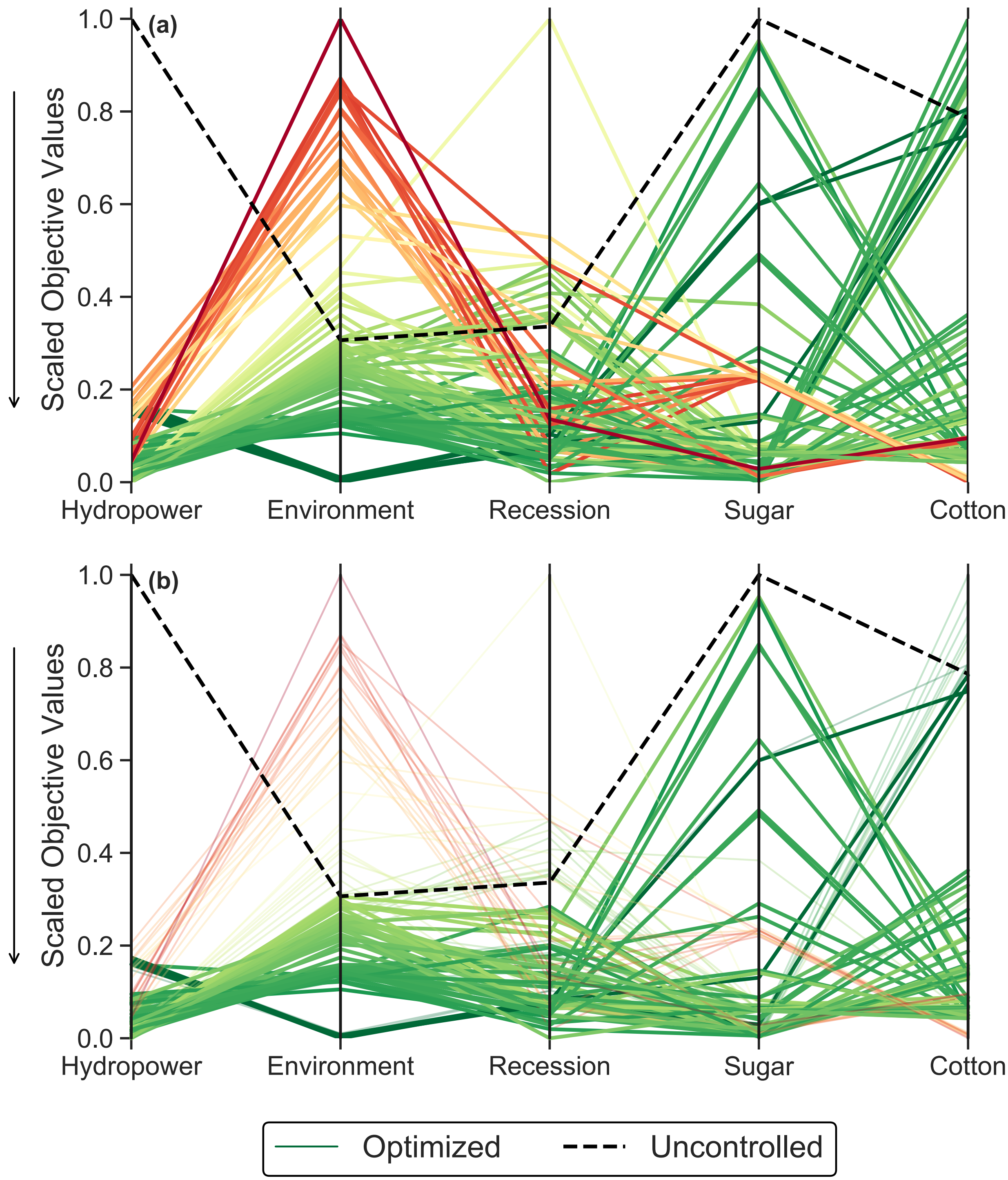

Fig. 2. (a) Parallel axis plots showing historical tradeoffs of operating policies under historical conditions. (b) The same parallel axis plot, but with policies that are outperformed by the historical uncontrolled conditions on at least one objective shown as transparent, and policies that outperform historical uncontrolled conditions on all objectives as opaque.

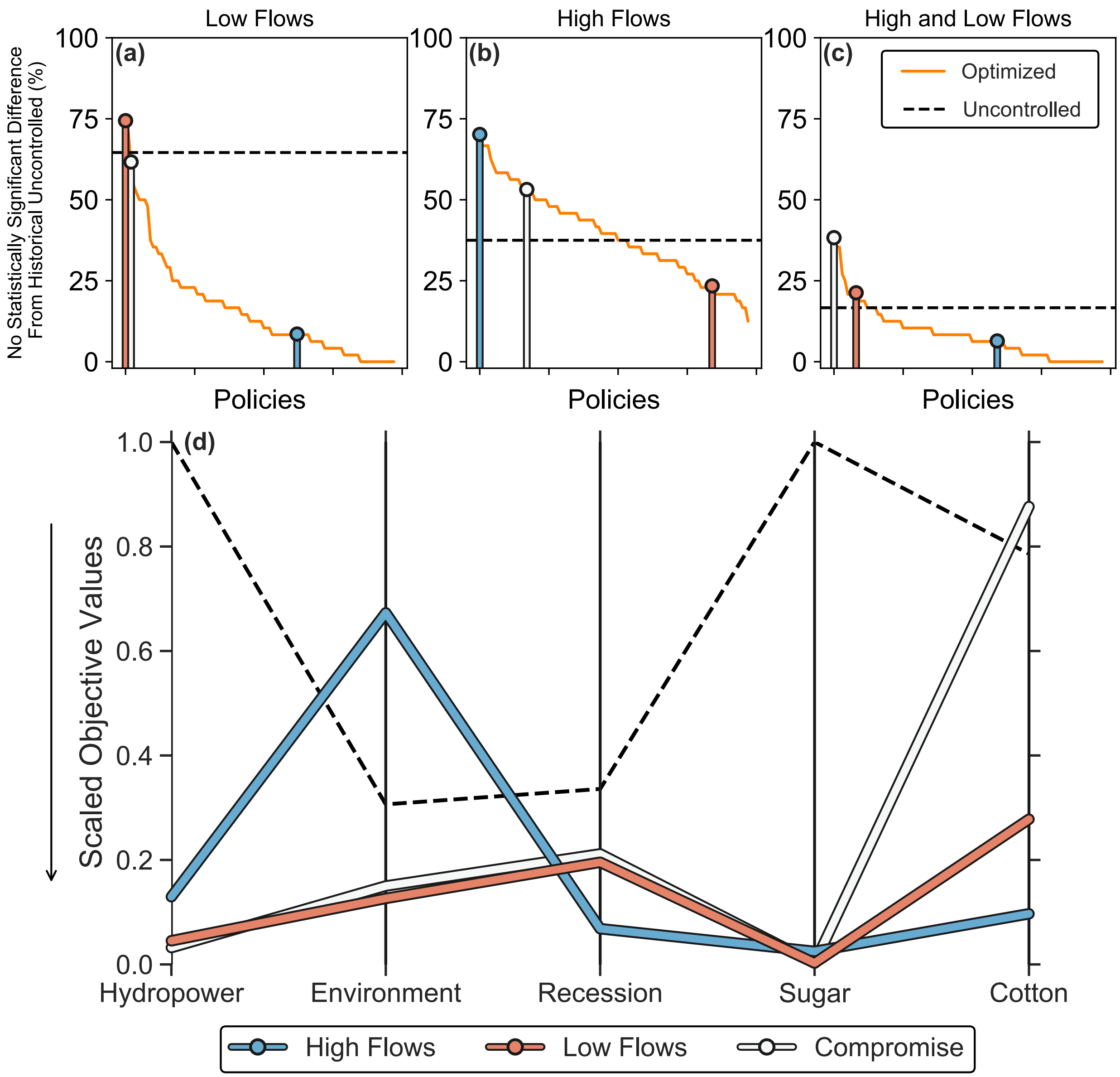

Fig. 3. (a) - (c) Performance on robustness metrics of all policies, sorted from highest to lowest on (a) 7QS, (b) AMS, and (c) both 7QS and AMS with policies that perform best on each metric highlighted. Policies with robustness metrics that are higher than the projected uncontrolled scenario (PUC) mitigate the impact of climate change while those with lower metrics exacerbate the impact of climate change. (d) Parallel axis plot showing historical tradeoffs of operating policies under historical conditions. Robust policies analyzed more deeply are highlighted.

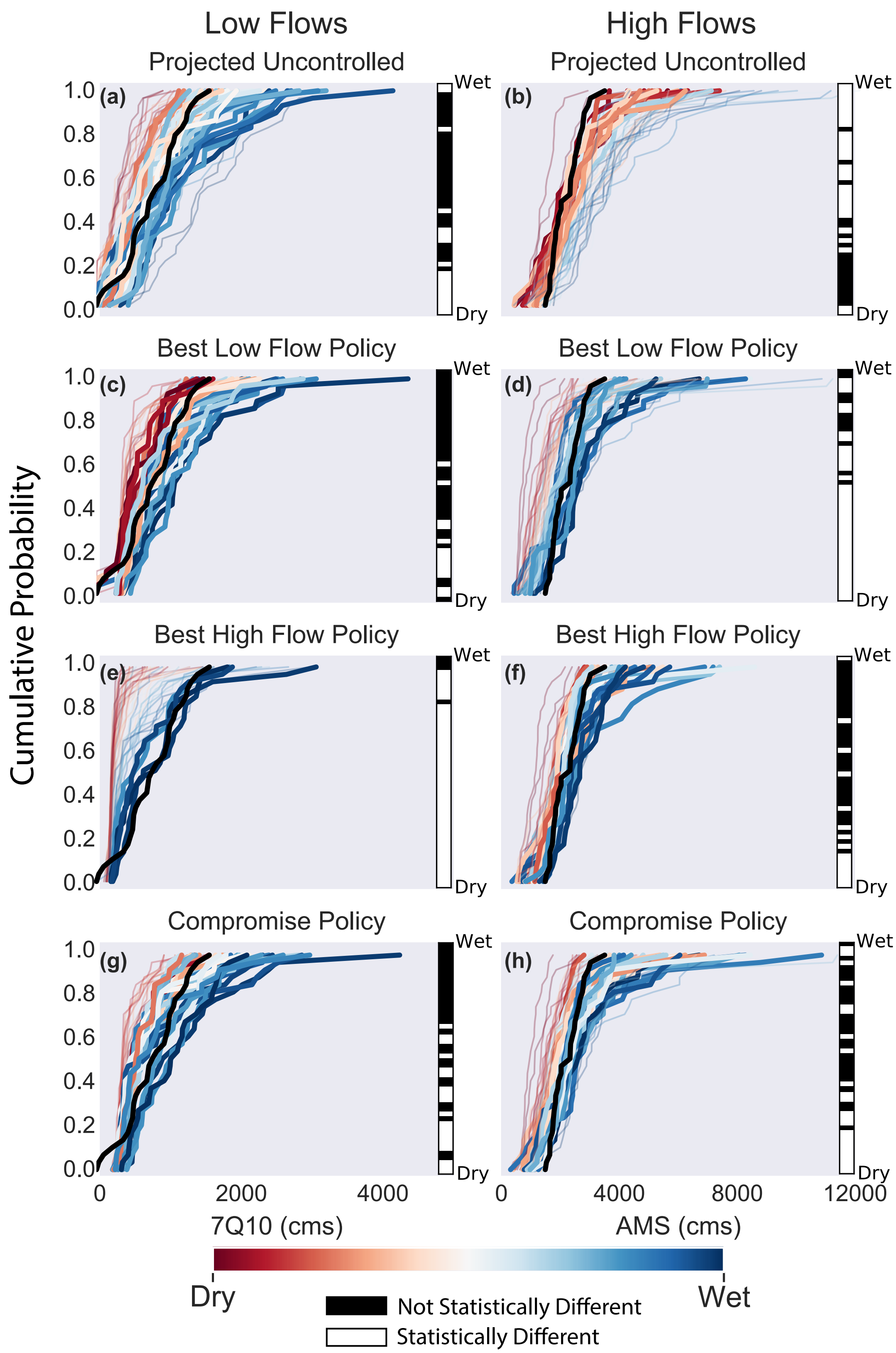

Fig. 4. Empirical cumulative distributions of seven-day low flows (left column) and annual maxima series (right column) for (a,b) projected uncontrolled conditions, (c,d) the Best Low Flow Policy, (e,f) the Best High Flow Policy, and (g,h) the Best Compromise Policy. The ECDFs of historical uncontrolled high and low flows are shown in black on each plot.

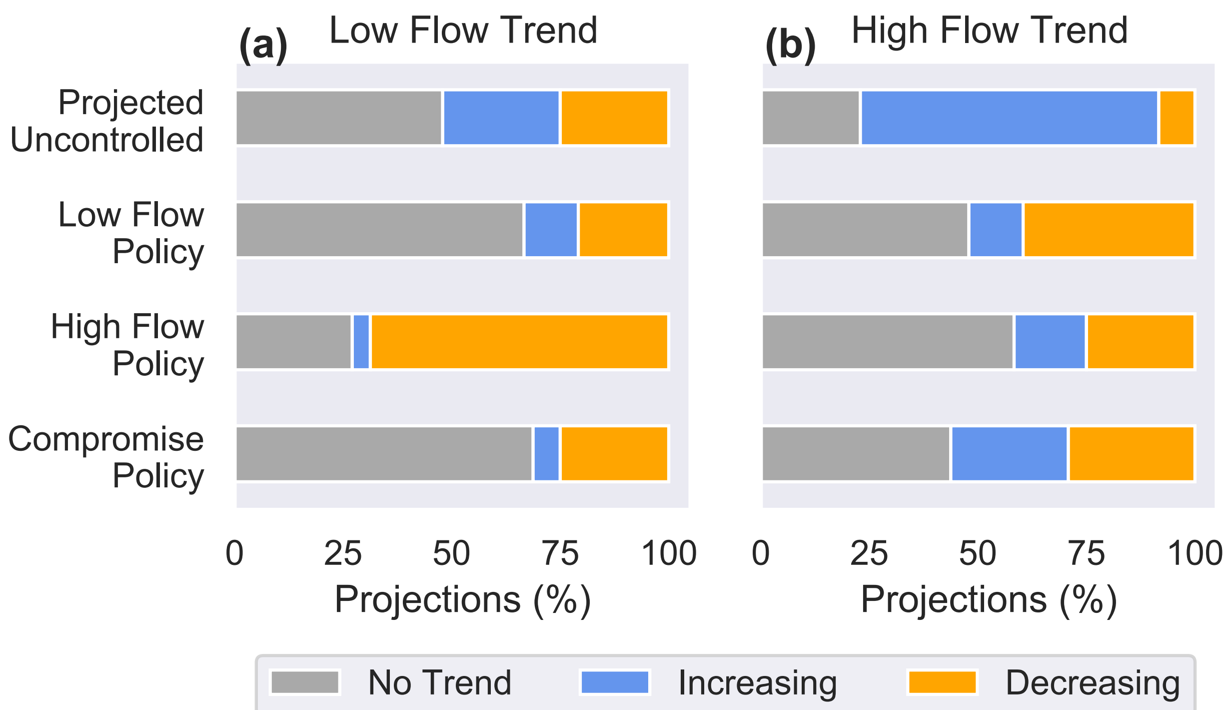

Fig. 5. Breakdown of the percent of projections that show no trend, an increasing trend, or decreasing trend for a projected uncontrolled scenario as well as for the best policy for preserving low flows, the best policy for preserving high flows, and the compromise policy that best preserves both high and low flows for (a) seven-day low flows, and (b) annual maxima series.

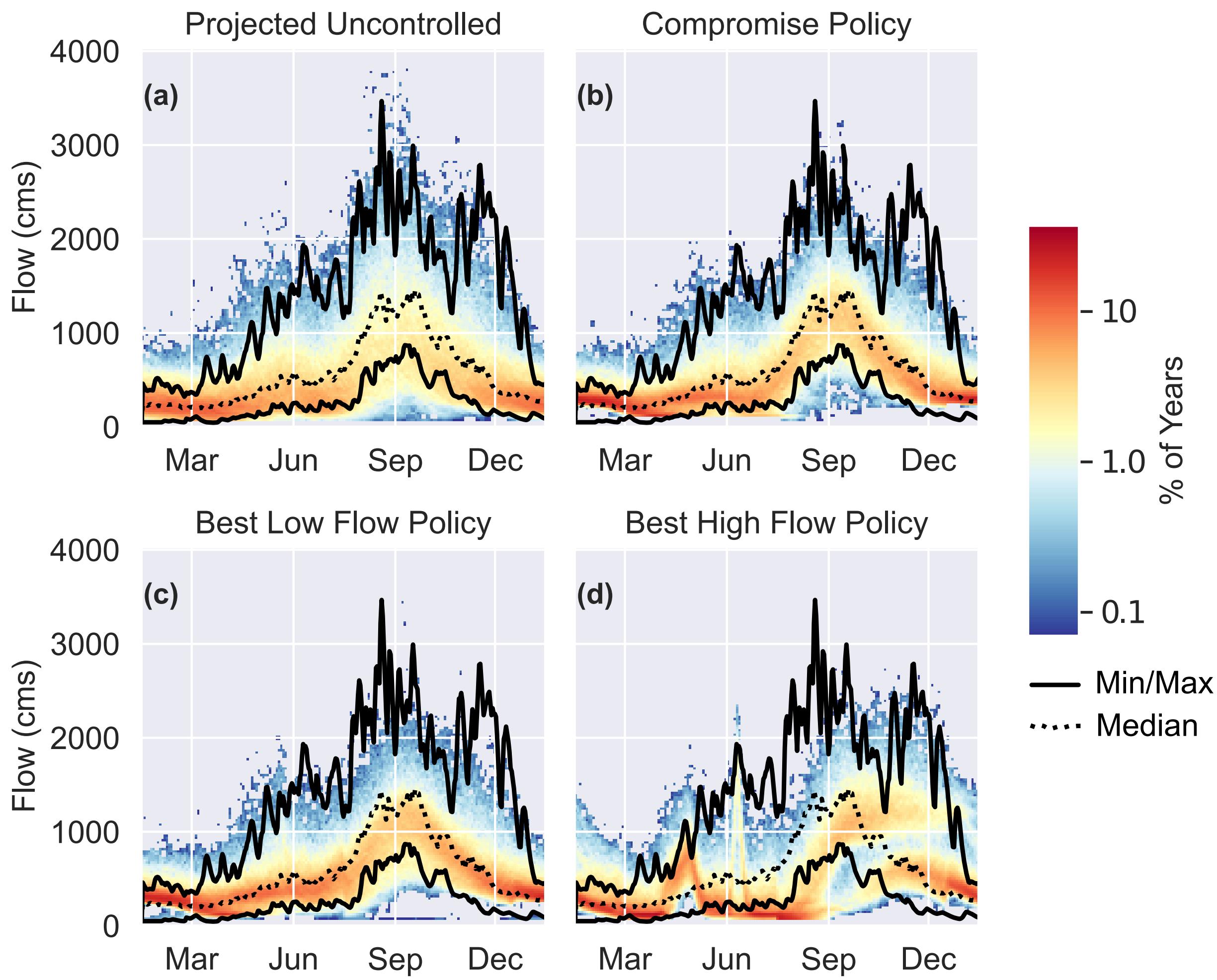

Fig. 6. The percent of simulated years where the flow was at different magnitudes on each calendar day, with high frequencies in red and low frequencies in blue for (a) a projected uncontrolled scenario, (b) the compromise policy (c) the best policy for preserving low flows, and (d) the best policy for preserving high flows. Maximum and minimum daily HUC flows are shown with the black solid line and the median daily HUC flows are represented by a dotted black line.

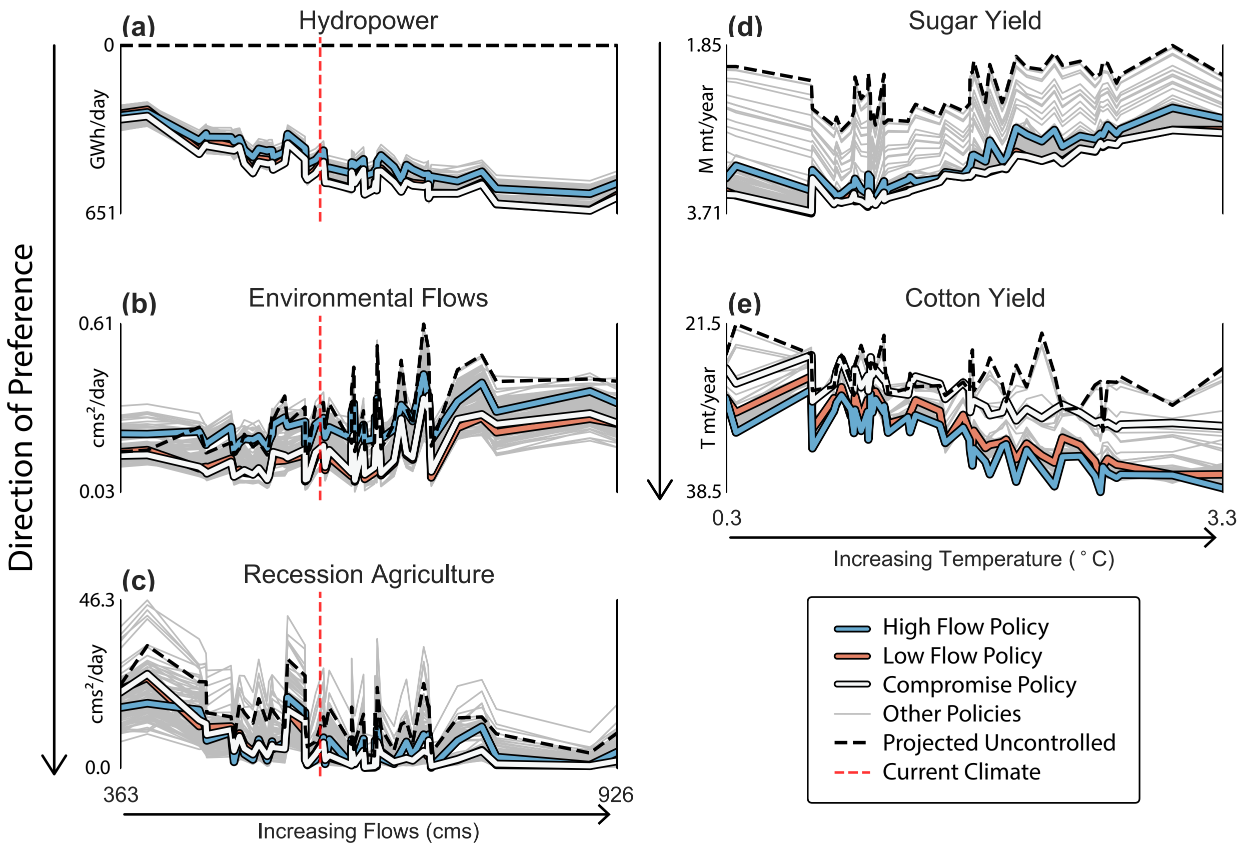

Fig. 7. Performance of the robust policies in 48 climate projections on (a) hydropower, (b) environmental flows, (c) recession agriculture, (d) sugar yield and (e) cotton yield (the remaining policies are shown in light gray). Projected average flows range from 363.4 to 926.1 cms, while historical average flows were 590 cms, denoted by the dashed red line in a-c. Projections that fall to the left of the red line are projected to be drier on average than the historical record, while those to the right are projected to be wetter. Temperatures are projected to increase between 0.26 to 3.34 degrees Celsius compared to historical temperatures. With a few exceptions, the robust policies generally perform better than the projected uncontrolled scenario across all climate projections.