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Participatory design of robust and sustainable development pathways in the Omo-Turkana river basin

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ABSTRACT

Study region: Omo-Turkana Basin, trans-boundary basin between Ethiopia and Kenya (North eastern Africa).
Study focus: Significant investments in large dams have been mobilized in the Omo-Turkana basin to expand hydropower and support extensive irrigation projects. Assessing the impacts of these infrastructures, particularly on local stakeholders, constitutes a crucial foundation for socially inclusive as well as environmentally and economically sustainable development. This study showcases the potential of a participatory decision-analytic framework in investigating the impacts of alternative development pathways on competing stakeholders' interests in the Omo-Turkana basin to support strategic planning under both current and projected hydroclimatic and socio-economic conditions. The optimal operation of the planned system expansion, including the current and future dam cascade and the irrigation projects, is investigated to provide insights into multisectoral trade-offs. Five main sectors with competing interests are considered: hydropower production, environmental protection, indigenous recession agriculture, fish yield in Lake Turkana, and large-scale commercial irrigated agriculture.
New hydrological insights for the region: Results show that the planned infrastructure can negatively impact local stakeholders, particularly in terms of fish yields in Lake Turkana. Still, a potential exists for negotiating operational compromises that are both efficient and socially inclusive. Moreover, even though the performance of the planned infrastructure is expected to decline in the future under changing climate and irrigation demands, this can be mitigated by timely implementing robust solutions triggered by the alterations of streamflows in the northern part of the basin.

1. Introduction

Global trends in population growth and rising economic prosperity increase the demand for energy, food, and water, with severe impacts, particularly in the Global South, where many economies are experiencing unprecedented growth rates (Jeuland and

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Whittington, 2014; Warner et al., 2019). The water available in many transboundary river basins constitutes a critical, largely untapped resource to foster the transformative change necessary to put sub-Saharan Africa on a path to sustainable growth that results in discernible progress in key Sustainable Development Goals such as poverty reduction, growth of income, food security, and electricity extension (IISD, 2019).

In this context, there is a growing consensus about the importance of developing multi-purpose water infrastructures for mitigating climate change and enhancing resilience to natural disasters (AfDB, 2020; UNESCO-UN-Water, 2020). Since many dams were designed as single-purpose infrastructures (Bertoni et al., 2019), properly assessing their multiple social, economic, and environmental impacts is crucial for promoting development pathways that are socially inclusive as well as environmentally and economically sustainable (OECD, 2017).

The uncertainty associated with future climate, socio-economic, and technological projections adds an extra layer of complexity to the development of long-term water resources planning strategies (Herman et al., 2020): the performance of a decision made now, strongly depends on the uncertain conditions that will unfold in the future (McPhail et al., 2018). Recently, several approaches have been proposed to identify robust solutions with respect to a large ensemble of deeply uncertain future conditions, i.e., whose probabilities are not known nor widely agreed upon (Herman et al., 2015). Despite some methodological differences in their implementation, these approaches share two common goals: (i) to identify robust solutions to deeply uncertain external factors and (ii) to discover the critical scenarios under which designed solutions can no longer satisfy minimum performance levels.

In this paper, we investigate the potential for a participatory decision-analytic framework in designing economically efficient, ecologically sustainable, and socially inclusive river basin development pathways under current and projected hydroclimatic and socio-economic conditions. Our framework is demonstrated for the Omo River-Lake Turkana Basin (OTB) shared by Ethiopia and Kenya. Lake Turkana is an endorheic lake in the Kenyan Rift Valley. Its northern end extends into Ethiopia close to the delta of the Omo River, which contributes most of the lake inflow volume. As part of the Ethiopian energy-security strategy, a number of dams are either operational or under construction along the Omo river (Zaniolo et al., 2021a). Yet, hydropower development in the basin is impacting several water-related sectors both in Ethiopia and Kenya, yielding social and international tensions (The Economist, 2016; Zaniolo et al., 2021b). Besides, in the coming years, large-scale agricultural production projects dependent on irrigation will be implemented in the Lower Omo region (Avery and Eng, 2012).

Since the beginning of the DAFNE project,[1] local stakeholders belonging to a wide range of public and private institutions, as well as to civil society organizations, have been involved in a series of Negotiation Simulation Labs (NSLs), a safe environment where participants had the opportunity to simulate a negotiation process and jointly discuss potential solutions, enabling the building of trust and social learning, while operating with integrity and transparency, exercising neutrality, and employing conflict resolution when needed (Lumosi, 2020). In the first NSL meeting, we interacted with several stakeholders from different sectors to identify candidate interventions and elicit their sectoral interests. These were later formalized into a selection of candidate development pathways and associated assessment indicators. Our definition of a pathway is a combination of structural and non-structural actions that generate alternative adaptation options to climatic and socio-economic changes (Haasnoot et al., 2012). A set of efficient pathways was then extracted from this candidate selection by optimizing the coordinated operation of water infrastructures in the OTB with respect to the multiple assessment indicators. The resulting solutions were discussed in a second NSL meeting that identified a small set of negotiated solutions among the efficient pathways as having the most interesting inter-sectoral trade-offs. Finally, the analysis of the latter was complemented by testing their robustness against a wide range of future uncertainties reflecting potential changes in both river flow regimes and water demands for irrigated agriculture.

Designing development pathways and assessing their sustainability across multiple sectors and over a range of infrastructural options and future climates goes beyond the scope of traditional cost-benefit analysis methods, which typically only focus on one infrastructure, one stakeholder and current hydrological conditions. Instead, the employed state-of-the-art robust, multi-objective, reinforcement learning-based optimization methods offer a computationally tractable approach to embed the system complexity and multi-stakeholder preferences in a comprehensive computational framework. Other than eliciting stakeholders' experience, part of the scope of the NSLs was to familiarize them with our models and build trust around the computational methods applied.

In summary, this paper provides two main contributions: a decision-analytic framework integrating several state-of-the-art approaches, including the analysis of model-based and synthetic scenarios that are often considered as alternative and mutually exclusive options; and a demonstration of this integration in the Omo-Turkana case study, where the active collaboration with local stakeholders enabled the co-production of relevant policy outcomes related to the discovery of multisectoral synergies, tradeoffs, and future vulnerabilities in this basin for prioritizing investments in projects.

The paper is organized as follows: the next section introduces the Omo-Turkana basin; Section 3 describes the participatory decision-analytic framework, including stakeholders' engagement and participation, development of the OTB model for assessing the performance of candidate development pathways, generation of future scenarios accounting for plausible and uncertain changes in both climate (i.e., precipitation, temperature, and streamflow) and irrigation demands. Modeling results and analysis are reported and discussed in Sections 4 and 5, while final remarks are presented in the last section.

[1] DAFNE – Decision Analytic Framework to explore the water-energy-food Nexus in complex transboundary water resource systems of fast developing countries (http://dafne-project.eu/).

2. The Omo-Turkana basin

In 1996, the Ethiopian government presented a master plan (Woodroofe, 1996) for developing the Omo Basin and exploiting its large hydropower potential by constructing the Gibe cascade (Table 1), a series of infrastructures complementing the already existing Gibe I dam (180 MW) and including Gibe II hydropower plant (420 MW), Gibe III dam (1870 MW), Gibe IV dam (1470 MW), and Gibe V dam (560 MW). In 2016, the construction of a new mega-dam named Koysha started (in place of the originally planned Gibe IV and V), which will add an installed capacity of 2200 MW to the cascade. In addition, in the coming years, the Lower Omo region is to be exploited for large-scale agricultural production in two separate districts (Table 2), with about 175,000 ha designated for irrigated sugar cane plantations, recently reduced to 100,000 ha, and about 80,000 ha for private commercial irrigated agriculture (Avery and Eng, 2012).

While the Ethiopian development strategy of becoming a significant exporter of energy and food in East Africa in the short to medium term (Zaniolo et al., 2021a) can be justified due to the accessibility of natural resources in the country, it is not clear whether the long-term sustainability of this strategy has been comprehensively assessed against current and future changes in climate and society. These infrastructures are already impacting several water-related sectors in Ethiopia and their downstream neighbor Kenya, yielding social and international tensions. The artificial regulation of the river can alter the hydrology of the Lower Omo, characterized by a late summer streamflow peak that overflows the riverbanks and supports crucial ecosystem services and food production strategies in the region. Among them, the streamflow peak enables flood recession agriculture practiced by nomadic or semi-nomadic tribes, fertilizes livestock grazing land, nourishes wetlands, and generates spawning areas for fish. There are also increasing concerns that the projected abstraction of river water for irrigation agriculture would lead to a significant and permanent drop in the lake Turkana level, with negative impacts for the local populations that depend on the lake services, especially in terms of fish yields (Avery, 2013).

While no central body exists for the governance of the shared watercourse of the OTB (Gibson and Yihdego, 2021), the Environmental and Social Impact Assessment conducted for Gibe III did consider transboundary impacts and proposed a number of mitigation measures (EEPCO, 2009). Such measures included the maintenance of a minimum flow release to meet the ecological requirements of the Omo and to mimic seasonal flooding with greater water release. However, due to the lack of discharge data from Gibe III, it is unclear whether any of these mitigation measures have yet been adopted.

3. Methods and tools

Building on Castelletti and Soncini-Sessa (2006), as part of the DAFNE project we developed a participatory decision-analytic framework to guide the development and selection of future pathways reconciling diverse water uses in the basin. Engagement with Ethiopian and Kenyan stakeholders from different sectors (see Supplementary material), including water and ecosystems, energy, food, socio-economy, and governance, began at the outset of the project using an actor analysis based on the approach proposed by Hermans (2005). This procedure ensured good coverage of all sectors in the aforementioned Negotiation Simulation Labs, as described in detail in Melenhorst et al. (2018). Three NSLs, involving approximately 20 stakeholders from Ethiopia and Kenya, were held annually between 2017 and 2019. In an initial NSL, sectoral interests were translated into a selection of candidate development pathways and led to the co-development of a suite of evaluation indicators to allow the comparative assessment of alternative pathways with respect to the interests of each group of stakeholders (Soncini-Sessa et al., 2007). The elaborated pathways include the construction of the Koysha dam and the development of two large-scale agricultural districts, along with the coordinated operations of the reservoirs' cascade and the irrigation diversions. A set of efficient pathways was subsequently designed by optimizing the OTB system operations for a subset of the evaluation indicators suggested by the stakeholders, called design indicators, selected as representative of the main stakeholders' interests. The resulting solutions were then negotiated in a second NSL meeting, in which the stakeholders were involved in the simulation of an interactive negotiation exercise that identified a small set of compromise solutions. No formal decisions were taken, as the participants had no official mandate, with the exercise intended as a demonstration of the methodology Finally, the analysis of the latter was complemented by testing their robustness against a wide range of future uncertainties about the potential changes in both flow regimes and irrigation demands. According to Matalas and Fiering (1977), a robust pathway is a solution that is as insensitive as possible to a large degree of uncertainty in the inputs and assumptions and therefore able

Table 1
Dams and power plants of the Gibe cascade. Data are from webuild (2018). Gray rows identify infrastructures eventually not built.

Dam	Year of construction	Hydraulic Head [m]	Installed/planned Capacity [MW]
Gibe I	1999-2004	40	180
Gibe II (power plant)	2004-2009	550	420
Gibe III	2006-2015	250	1870
Gibe IV	Not built	-	1470
Gibe V	Not built	-	560
Koysha	2016-in progress	178.5	2200

Table 2
OTB large-scale agricultural districts. Data are from Avery (2013).

Agricultural district	Targeted Irrigated area (ha)	Crop	Average water demands [m^3/s]
Kuraz sugar plantation	100,000	Sugar cane	180
Private commercial agriculture	~ 80,000	Mixed cultures	34

to ensure robust performance across multiple plausible futures, generally represented by an ensemble of climate (i.e., precipitation, temperature, and streamflow) and socio-economic scenarios (i.e., irrigation demands). The robustness of the efficient pathways is evaluated against a first ensemble of scenarios obtained following a scenario-led approach (Wilby and Dessai, 2010), which relies on a cascade of models from global Representative Concentration Pathways (Moss et al., 2010) to local hydrologic conditions. We considered both RCP4.5 and RCP8.5 in order to capture the large uncertainties characterizing the future evolution of the climate system. Besides, following the taxonomy for robustness frameworks suggested by Herman et al. (2015), our analysis also includes the generation of a second, larger ensemble of synthetic scenarios, which is used to complement the analysis of robustness and identify via scenario discovery the most critical drivers under which the system is expected to fail (i.e., a pathway does not meet pre-specified performance criteria). The results, discussed in a third NSL meeting, eventually allowed the identification of possible development pathways able to address the multisectoral tradeoff in the basin while sustaining a robust performance under changing climate and society.

3.1. Stakeholders participation

The participatory approach adopted in DAFNE entailed that candidate actions (which represent the building blocks of the candidate pathways), as well as evaluation and designed indicators, were identified collaboratively during the NSLs, which represented a safe environment to facilitate interactions between local stakeholders and project partners. Local stakeholders possess deep knowledge and understanding of the multisectoral dynamics in the OTB, which complemented the technical expertise of project partners in modeling the system and the different interests impacted by the pathways under evaluation.

The first NSL (see Fig. 1) represented the starting point for the process of identification of the candidate actions and evaluation indicators, which was structured in 4 steps:

1. An interactive mapping exercise was run to identify issues related to the diverse stakeholders' interests, single out actions able to solve or influence the identified issues, and collect proposals of relevant evaluation indicators able to measure the effects of these actions.

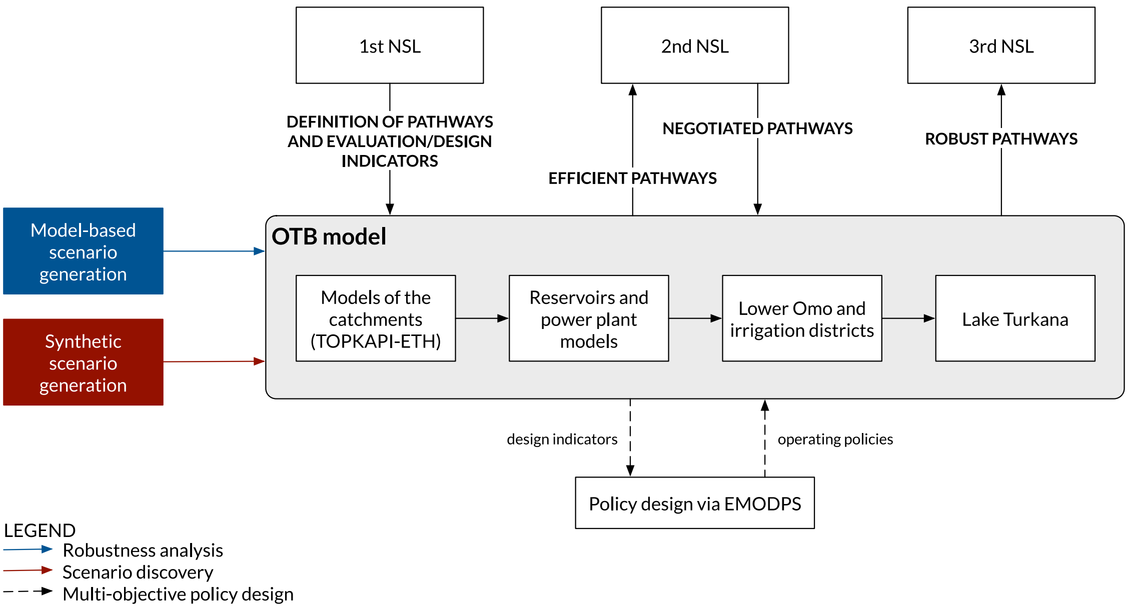


Fig. 1. Illustration of the participatory decision-analytic framework, highlighting the main interactions with the stakeholders during the NSLs. The blue and red boxes show the generation of climate and irrigation demand scenarios supporting the robustness analysis and the scenario discovery. The dashed lines show the multi-objective policy design. Technical details about each framework component are provided in the following sub-sections.

2. The outcomes of the mapping exercise were structured into tables reporting all the issues, actions, and evaluation indicators identified, grouped according to different sectorial interests (e.g., energy, food, etc.).
3. Contents of the tables were subsequently elaborated through an iterative process driven by criteria of relevance for the specific OTB context and feasibility with respect to available data and modeling tools. These elaborations also included the selection of a subset of evaluation indicators, called design indicators, to be used for the design of efficient pathways. This process took part both in presence and remotely, involved DAFNE partners and local stakeholders, and was supported by a number of participatory tools developed within the project.
4. A consolidated list of evaluation and design indicators, candidate actions, and pathways was eventually defined and shared online with all stakeholders to be available for further references and ensure the possibility of continuous exchange of related comments and information.

The following set of design indicators, which can be used as objective functions in designing the efficient pathways using the system model described in Section 3.2, were selected from the list of evaluation indicators:

- Hydropower production (J^{HP} [GWh/year]): maximization of the mean annual hydropower production at the basin level, i.e., the cumulative production of all the power plants;
- Environment in the Omo delta (J^{E} [$(m^3/s)^2$]): minimization of the average squared deviation of the simulated inflow in the Omo delta at the town of Omorate under a given pathway with respect to the natural hydrograph (blue line in Fig. 2). This indicator measures the alteration of the natural flow conditions in the ecosystem of the Omo delta, penalizing both positive (more water) and negative (less water) deviations from the natural regime;
- Recession agriculture (J^{R} [$(m^3/s)^2$]): minimization of the squared streamflow deficit with respect to flow requirements reported in Avery and Eng (2012) needed to practice flood recession agriculture in the lower Omo valley (orange line in Fig. 2);
- Fish in Lake Turkana (J^{F} [MT]): minimization of the deviation of annual fish biomass in Lake Turkana under a given pathway with respect to natural conditions. The adopted worst-case formulation is motivated by the observation that several indigenous communities resort to fishing exclusively in exceptionally dry years when other survival strategies fail to provide sustenance. According to Gownaris et al. (2017), the fish biomass is estimated from the daily trajectories simulated by the model as a function of the average Lake Turkana water level in the previous year and the amplitude of lake level oscillation in the current year between dry season (January–August) and wet season (September–December);
- Irrigation (J^{I} [-]): minimization of the average deficit of irrigation water at the basin scale computed by aggregating the normalized deficits occurring in the two irrigation districts (i.e., Kuraz sugar plantation and private commercial agriculture). The deficit is computed using the values of irrigation demand from Table 2 in the analysis conducted under observed conditions, while demand projections (see Section 3.3 and Supplementary Fig. S3) are considered for testing the robustness of the efficient pathways.

3.2. The OTB model

The OTB model is a conceptual model composed of the following building blocks (see Fig. 3): three artificial reservoirs with associated hydropower plants, namely Gibe I (GI), Gibe III (GIII), and Koysha (K), the Gibe II (GII) hydropower plant that is connected to GI through a diversion tunnel, two irrigation districts (i.e., Kuraz sugar plantation and private commercial agriculture), Lake Turkana (T), and all the river stretches connecting these elements.

Artificial reservoirs and Lake Turkana dynamics are modeled through a mass balance equation of the corresponding water storage

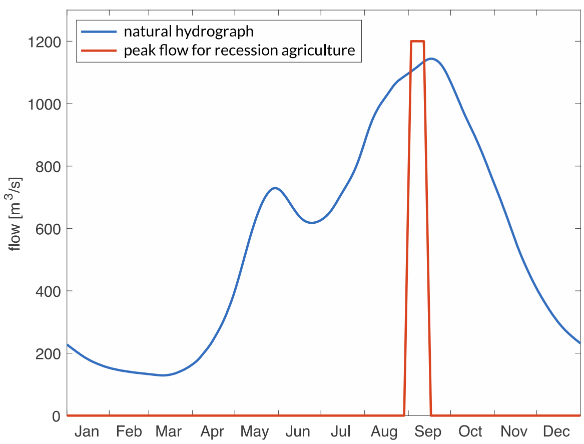
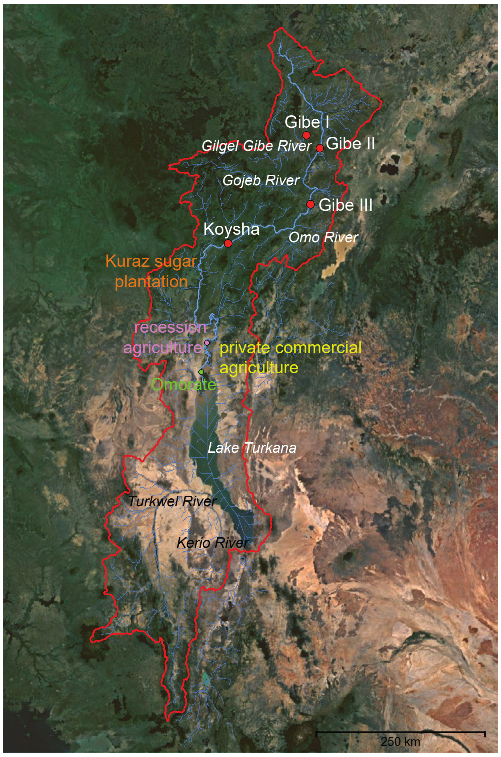


Fig. 2. Cyclostationary trajectory of natural flow regime in the Omo delta (blue line), computed averaging the streamflow in the delta simulated for the pristine system (no dams) over 1985–2001. Target flow requirement in the lower Omo valley for recession agriculture (orange line) according to Avery and Eng (2012).



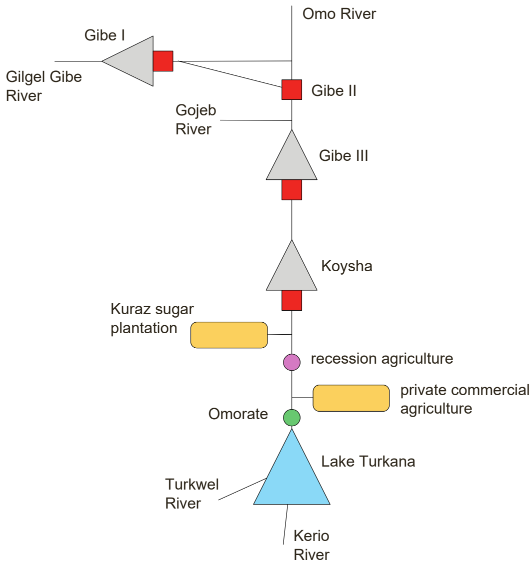


Fig. 3. OTB map (left) schematic representation of the main components of the OTB model (right).

using a daily time step:

$$s_{t+1}^{GI} = s_t^{GI} + q_{t+1}^{GI} - e_t^{GI} A_t^{GI} - r_{t+1}^{GI}$$

$$s_{t+1}^{GIII} = s_t^{GIII} + q_{t+1}^{GIII} - e_t^{GIII} A_t^{GIII} - r_{t+1}^{GIII}$$

$$s_{t+1}^{K} = s_t^{K} + q_{t+1}^{K} - e_t^{K} A_t^{K} \quad - r_{t+1}^{K}$$

$$s_{t+1}^{T} = s_t^{T} + q_{t+1}^{Delta} + q_{t+1}^{Turkw} + q_{t+1}^{Ker} \quad - e_t^{T} A_t^{T}$$

where s_t^i ($i =$ GI, GIII, K, T) is the water storage in the i-th reservoir and Lake Turkana at the beginning of day t, while, $q_{t+1}^i, r_{t+1}^i, e_t^i A_t^i$ are the inflow to the reservoir, the volume of water released (including spills), and the water evaporated in the time interval $[t; t+1)$, respectively. In particular, e_t^i is the average daily evaporation rate computed according to the equation proposed by Priestley and Taylor (1972) and A_t^i is the reservoir surface area uniquely defined for each reservoir and the lake by a non-linear storage-surface area relation given s_t^i. Seepage losses are considered negligible. In the adopted notation, the time subscript of a variable indicates the instant when its value is deterministically known. The release of the j-th artificial reservoir ($j =$ GI, GIII, K) is defined as $r_{t+1}^j = f\left(s_t^j, u_t^j, q_{t+1}^j, e_t^j\right)$, where $f(\bullet)$ describes the non-linear relation between the release decision (u_t^j), determined by a candidate operating policy as a function of a vector of inputs such as reservoirs' storage, and the actual release (r_{t+1}^j) (Soncini-Sessa et al., 2007). The actual release at the end of the time interval is generally equal to the release decision unless physical constraints prohibit it, for instance, because of the activation of the spillways. Lake Turkana, instead, is an endorheic lake; therefore, the only outgoing water is due to evaporation.

It is worth mentioning that the model does not include the Turkwel dam as its operation is independent of the strategy adopted for managing dams and irrigation diversion along the Omo River. Moreover, the only indicator potentially impacted by this dam operation is the fish in Lake Turkana, which however depends on the average annual lake level and its associated seasonal variations that are minimally affected by the Turkwel dam operation given the limited reservoir capacity and the limited annual streamflow compared to the ones along the Omo River.

According to the daily time-step adopted in the model, the river reaches are modeled as plug-flow canals, in which the velocity and direction of flow are constant everywhere, without any routing effect. Transit lag times from Gibe I to Gibe III (3 days), Gibe III to Koysha (6 days), and Koysha to Lake Turkana (12 days) are estimated as the average time required by the water to transit between the two points.

The inflows from the Gilgel Gibe, Omo, Gojeb, Turkwel, Kerio rivers, and the lateral contributions upstream and downstream of Koysha were estimated using the TOPKAPI-ETH model, a spatially distributed hydrological model that extends the original TOPKAPI rainfall-runoff model of Liu and Todini (2002), by adding several additional model components. TOPKAPI-ETH performs a spatial and temporal representation of the main hydrological processes at the basin scale. Spatial heterogeneity is represented by discretizing the domain with a regular grid of 1 km^2 of resolution, while the temporal dynamics are characterized at a daily time step. The model inputs are daily values of precipitation from the TRIMM 3B42 archive (Huffman et al., 2007) and model reanalysis temperature and cloud cover records from MERRA-2 (Reichle et al., 2017). Due to the limited availability of observed flow records in the catchment, the model calibration followed a two-stage process. First, a calibration was carried out against the Abelti gauging station in the upper reaches of the Omo catchment downstream of the Gibe I dam. This was to develop some confidence in the flows modeled in respect of the timing of response to rainfall and recession behaviors. The second phase of model calibration was to calibrate the model parameters most affecting the catchment water balance to achieve a good representation of the daily historical levels of Lake Turkana as observed by satellite altimetry (Cretaux et al., 2011). The comparison of observed and simulated levels of Lake Turkana is reported in the Supplementary Fig. S1; the correlation between modeled and observed levels is 0.93, while the RMSE of the lake levels is 0.34 m.

All investigated development pathways for the OTB include the planned construction of both the Koysha dam and the large-scale agricultural districts. Still, they differ depending on the overall operations of the network of dams (i.e., Gibe I, Gibe III, and Koysha) and the two irrigation diversions. The strategies determining the coordinated operations of the system are modeled as a closed-loop operating policy (Castelletti et al., 2008). In the absence of publically available operating rules and considering that all dams are controlled by the Ethiopian Electric Power Corporation, we assumed that the optimal coordinated operation is a plausible representation of a rational policy that the could be implemented for operating the system when the construction of Koysha dam will be completed. Such policy determines the dam release decisions as a function of the storage in each of the three reservoirs, along with the sine and cosine of the day number of the year to capture the seasonality of the inflows as well as of the environmental and flood recession flow requirements. Specifically, this policy is defined as a non-linear approximating network using Gaussian radial basis functions with five inputs (i.e., sine and cosine day of the year and three reservoir storages), 9 Gaussian bases, and 3 outputs (i.e., releases from Gibe I, Gibe III and Koysha), for a total of 120 policy parameters. In addition, the diversion channels that abstract water from the main Omo river to provide irrigation to the two agricultural districts are regulated according to two non-linear hedging rules (Celeste and Billib, 2009), which allows diverting into the irrigation canals less water than their corresponding demands to compensate for downstream users. Each hedging rule depends on 2 additional parameters.

Formally, the set of Pareto approximate operating policies p_θ^* is then generated by solving the following multi-objective optimal control problem:

$$p_\theta^* = argJ \quad = | -J^{HP}, \quad J^E, \quad J^R, \quad J^F, \quad J^I |$$

where the policy parameters are searched in the decision space $\theta \in \Theta$ and the problem is constrained by the system's dynamics.

This problem is solved via Evolutionary Multi-Objective 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 advantage of using EMODPS against other optimal control methods (Giuliani et al., 2021) is the possibility of designing the coordinated control across multiple reservoirs alleviating the well-known curse of dimensionality (Giuliani et al., 2018). Moreover, EMODPS enables the computation of an approximation of the Pareto front in a single run of the algorithm, which supports the exploration of multidimensional trade-offs between conflicting objectives (Giuliani et al., 2014). To perform the optimization, we use the Borg MOEA (Hadka and Reed, 2013), which has been shown to be highly robust in solving multi-objective optimal control problems (Zatarain-Salazar et al., 2016). Each optimization was run for 2 million function evaluations. To improve solution diversity and avoid dependence on randomness, the final set of Pareto optimal policies is obtained as the set of nondominated solutions identified from 10 random optimization trials. In total, the 20 million simulations required around 1600 computing hours. Each optimization run was parallelized over 128 processing cores of The Cube Cluster of Cornell University, a 512 processing cores system with a 120 Terabyte Terascale file system.

3.3. Future scenarios

The model-based generation of future scenarios (blue box in Fig. 1) produced an ensemble of 600 scenarios, obtained as the cartesian product of 60 climate projections and 10 irrigation demand scenarios. For the two considered Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5, a 30-member ensemble of climate scenarios over the period 2020–2100 is generated via stochastic downscaling of the climate trajectories simulated by different combinations of General Circulation Models (GCMs) and Regional Circulation Models (RCMs) to refine the coarse spatial resolution of GCMs and RCMs as well as to obtain an ensemble that includes the internal climate variability in addition to the general changes from the climate models, which would not be represented by a single run of the climate models (Fatichi et al., 2016). Specifically, factors of change are estimated by comparing the climate variables simulated by the 22 members ensemble of RCM-GCM models (i.e., 10 GCMs and 6 RCMs, but not all combinations are available) over the historical control period (1976–2005) with seven 30-year time windows of projected climate simulated by the same climate models in time blocks from 2010 to 2039 through to 2070–2099. The estimated factors of change are then applied to the stochastic simulations of the historical climate produced by the AWE-GEN-2d model (Peleg et al., 2017), a two-dimensional downscaling weather generator, to generate an ensemble of future climate realizations including precipitation, near-surface air temperature, solar radiation, wind speed, and relative humidity at the same space and time scales of the stochastic weather generator (Peleg et al., 2019). The median change in precipitation and potential evapotranspiration based on the Penman-Monteith formulation (Allen et al., 1998) computed over the 30-member ensemble produced by AWE-GEN-2d between (1976–2005) and (2070–2099) time periods under the RCP8.5 is reported in Supplementary Fig. S2. Subsequently, 30 realizations of the daily streamflow sequences for each of the two RCPs were generated using the TOPKAPI-ETH model by combining downscaled precipitation and evapotranspiration ensembles.

Future irrigation demand scenarios were generated by simulating planned irrigation schemes using the AquaCrop model (Steduto et al., 2009) using the projected precipitation and temperature trajectories for both RCP 4.5 and 8.5, along with soil characteristics from ISRIC soil grids, default crop parameters, assuming a 45% and a 58% irrigation efficiency. These reference values for irrigation efficiency are obtained by combining conveyance efficiency and field application efficiency provided by Brouwer et al. (1989). The resulting trajectories of irrigation demands were then synthetically perturbed using scaling factors (i.e., ± 5% and ± 10%) to include a wider range of plausible future irrigation abstractions to account for model errors and uncertainty in input data and assumptions. The generated ensemble of irrigation demand scenarios is reported in Supplementary Fig. S3 as a cyclostationary mean for 2020–2099.

To exhaustively and uniformly explore the drivers' space for informing the scenario discovery analysis, we complemented the ensemble of model-based scenarios described in the previous section with a new synthetically generated ensemble of 15,000 scenarios (red box in Fig. 1). According to the methodology originally introduced by Quinn et al. (2018), the future inflows are produced using a synthetic streamflow generator that explores changes in several statistics of streamflow abundance and timing. Starting from daily observed streamflow time-series, it produces correlated synthetic daily streamflow series at multiple sites assuming stationarity in hydrologic processes. The goal of this first step is to artificially expand the historical observational dataset by generating statistically equivalent data for a more in-depth exploration of the natural processes' variability. Secondly, a non-stationary generator is employed to alter the synthetic series imposing trends on historical climate, including monthly varying mean and standard deviation multipliers. In addition, changes in streamflow timings are generated by applying time-varying multipliers to Fourier series fitted to the historical log-space monthly mean flows. Finally, the future agricultural water demands are generated via global sampling of scaling factors within a range of ± 30% with respect to the historical values.

This large ensemble of scenarios is then used to perform scenario discovery through the Patient Rule Induction Method (Friedman and Fisher, 1999), a data mining technique that has been adopted in many recent robust decision-making studies (e.g., Trindade et al., 2017) to identify critical ranges of uncertain drivers where system failures are likely to occur. PRIM returns alternative sub-sets of scenarios delimited by failure boxes that are identified by maximizing two conflicting metrics: (i) density, i.e., the ratio of the number of cases of failures inside a candidate box to the total number of scenarios inside that box, and (ii) coverage, i.e., the ratio of the number of failures inside a candidate box to the total number of failures in the entire ensemble of scenarios. In an interactive process, PRIM suggests alternative candidate boxes that lie on a Pareto optimal surface described by the two metrics from which the users can navigate the trade-off curve to select a specific result. For more details, see Bryant and Lempert (2010).

4. Results

4.1. Trade-off analysis

The performance of each pathway is estimated via simulation of the OTB model over the historical horizon (2002–2016). The performance of the Pareto efficient solutions is depicted in Fig. 4. Each line in the parallel axes plot represents the performance of one pathway across the different design indicators represented by the 5 vertical axes, namely Hydropower, Environment, Recession, Fish, and Irrigation. The indicator values are normalized between 0 and 1, where the values equal to 0 and 1 correspond to worst and best performance over the set of pathways, respectively, as indicated by the upward preference arrow (e.g., Hydropower = 0 means that the pathway has an average production of 632.92 GW h/y, whereas Hydropower = 1 corresponds to a pathway with an average

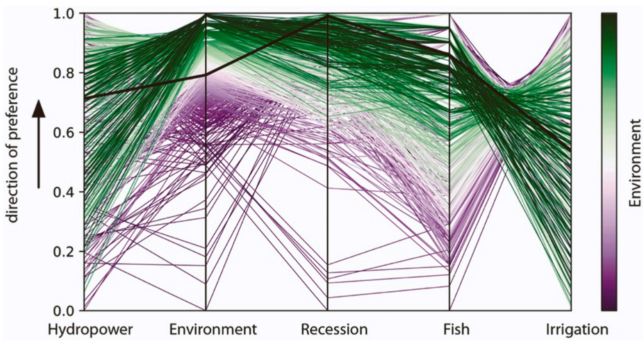


Fig. 4. Performance of the Efficient Pathways over the historical horizon 2002–2016. In the parallel axes plot where the indicator values are normalized between the minimum and maximum performance over the set of pathways, and the axes are oriented so that the direction of preference is always upward. Lines color are assigned based on the Environment indicator, where green lines indicate good performance and purple lines indicate poor performance. The bold black line is one of the pathways negotiated by the stakeholders during the second NSL meeting and will be investigated in the robustness analysis.

production of 873.18 GW h/y). A horizontal line laying at the top of the graph would thus correspond to a pathway that fully satisfies all stakeholders. However, such a solution is unattainable for the system, given the presence of conflicts among water uses, designated as diagonal lines between two adjacent axes. Lines are colored by the Environment indicator, measuring the deviation of the simulated flow in the Omo delta under a given pathway with respect to the natural regime, with a color scale that ranges from green (best solution) to purple (worst solution).

Results show a clear conflict between Hydropower and Irrigation on the one hand and Environment, Recession Agriculture and Fish on the other. Almost parallel lines in the uppermost portion of the Environment, Recession Agriculture, and Fish axes show that solutions preserving the environment in the Omo delta (green lines) are generally good also in terms of recession agriculture and fish in Lake Turkana as all these indicators tend to restore the natural flow conditions. Conversely, the best hydropower production and irrigation supply pathways are purple lines scattered in the center and lower region of the Environment axis. Notably, the sharpest conflict is between Irrigation and Fish indicators. The water abstracted and consumed for irrigation no longer contributes to Lake Turkana inflows, negatively impacting the ecosystems supporting fish reproduction. Lastly, Hydropower and Irrigation do not seem to conflict, indicating that the system appears well-designed for maximizing the economic return of the water resources in the basin. At the same time, the costs of this solution for the environment and local activities in the Lower Omo region are expected to be significant and largely overlooked by traditional planning procedures that often fail to address the trade-off between economic development and long-term sustainability.

Despite the existence of conflicts, the abundance of efficient pathways reported in Fig. 4(i.e., 848 alternative solutions) represents a rich context for supporting the identification of compromise solutions. During the 2nd NSL meeting, stakeholders from different countries and sectors analyzed the whole volume of options to converge toward one compromise solution. They were involved in an interactive session, in which they simulated a negotiation exercise iteratively filtering the set of pathways and eventually identified a set of six negotiated solutions. Notably, the iterative process leading to the selection of interesting alternatives during the negotiation substantially reduced the risks of producing unbalanced outcomes due to the existing variability of stakeholders' economic importance and political relevance because this strategy ultimately simulates different power dynamics among sectors without assuming necessarily reproducing the real one. However, Kleinschroth et al. (2021) examined potential power dynamics using the concept of narratives and concluded that such underlying narratives should be explicitly accounted for in stakeholder engagements. In the rest of the paper, we will focus on one of these negotiated solutions, selecting the compromise pathway which provides the most balanced trade-off across all the five design indicators (see the bold black line in Fig. 4). This stakeholders' negotiated pathway produces the indicator values reported in Table 3, which also includes the best and worst values of the design indicators as a reference. Consistently with the visual analysis in Fig. 4, we can notice that this pathway performs very well (i.e., top 1% of the solutions) in terms of Recession agriculture, with an annual streamflow deficit equal to 87 m^3/s against a target requirement to practice recession agriculture of 16, 800 m^3/s, thus ensuring more than 99% of the considered target. This pathway is in the top 20% of solutions for both Environment and Fish, as it provides about 70% of the natural water flow regime in the Omo delta and 6.8 M tonnes of fish in Lake Turkana (i.e., 85% of the yield in natural conditions). The performance in terms of Hydropower is relatively good, namely in the top 30% of the designed pathways; the estimated average production of 8578.6 GW h/y could satisfy 86% of the total Ethiopian energy use in 2017 (i.e., 10 TW h (International Energy Agency, 2019)), assuming electricity is used for internal consumption. Lastly, Irrigation is the indicator with the lowest performance with a value of normalized deficit that is 45% higher than the best possible performance in this indicator.

4.2. Robustness analysis

To evaluate the potential vulnerabilities of the 848 efficient pathways illustrated in Fig. 4 to changes in climate and socio-economic conditions, we ran a Monte Carlo simulation of the OTB model for all these alternative pathways over the 600 member ensemble of model-based generated scenarios (see Section 3.3). Fig. 5 provides a synthesis of the outputs of these 508,800 simulations by computing the Empirical Cumulative Density Function (ECDF) of the pathway performance across the five design indicators. In the plot, the vertical axis reports the fraction of plausible futures that achieves or exceeds the performance level shown on the horizontal axis. Hence, the worst value of each indicator is achieved or exceeded in 100% of scenarios, and the best value only for one scenario. This strategy allows exploration of a multidimensional satisfying surface a posteriori, rather than specifying acceptable performance thresholds a priori (Bertoni et al., 2019).

In all subplots, the different lines are fairly close to each other, indicating a contained variability across different pathways. On the contrary, the difference between a given pathway's best and worst performance spans a much larger range. This implies that when system operation is designed to be efficient under a given scenario, the uncertainty in the future performance is largely driven by the

Table 3
Performance of the stakeholders' negotiated pathway with respect to the 5 design indicators, along with best and worst indicator values found in the set of pathways, corresponding to the normalized values 1 and 0 in Fig. 4.

	Hydropower [GW h/y]	Environment $[(m^3/s)^2 * 10^6]$	Recession $[(m^3/s)^2 * 10^3]$	Fish [MT]	Irrigation [%]
Stakeholders' negotiated pathway	8578.6	30.74	7.63	1.21	0.88
Best value in the set of efficient pathways	9313.9	11.07	0	0.47	0.04
Worst value in the set of efficient pathways	6751.2	105.89	774.35	5.78	1.87

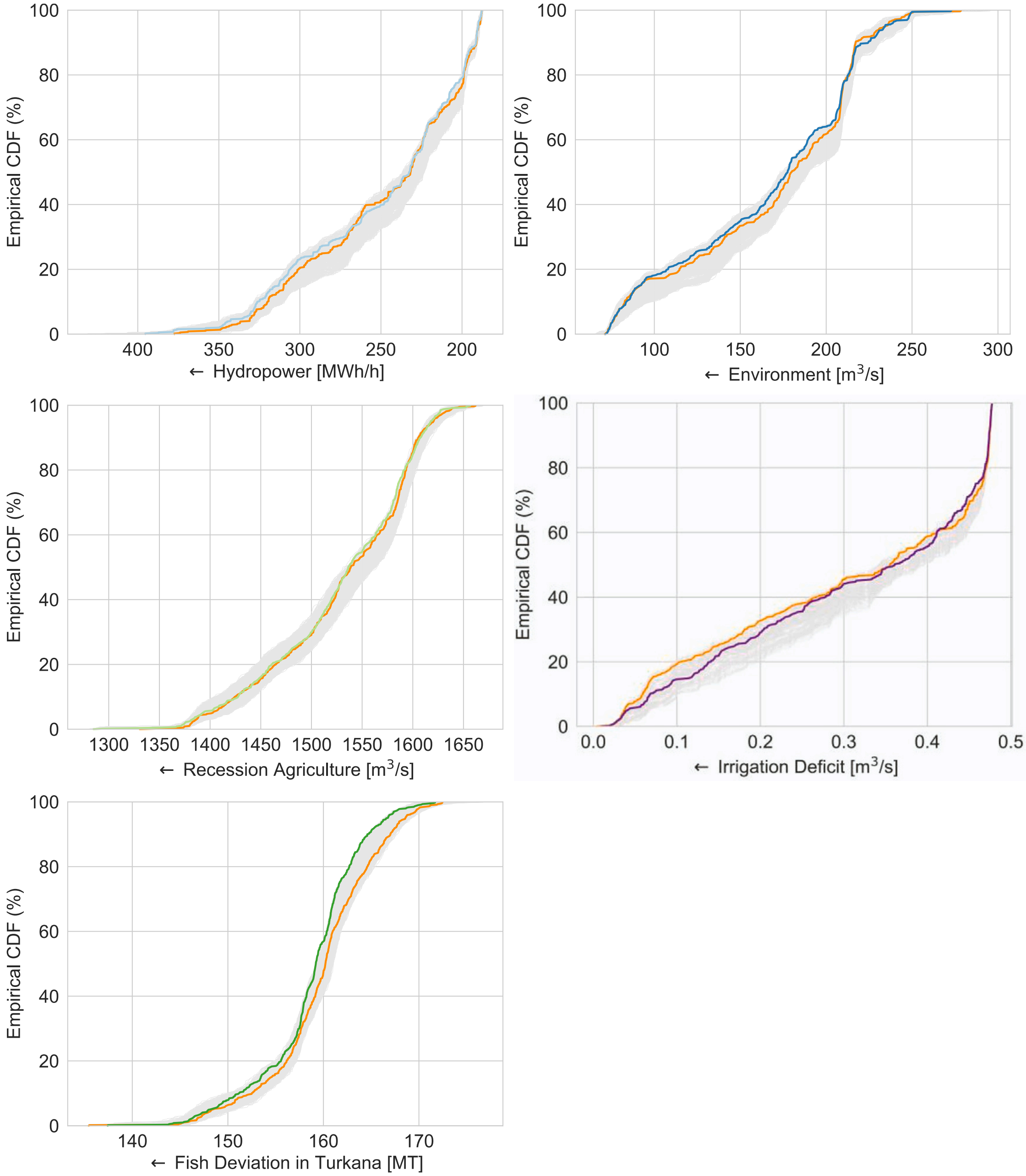


Fig. 5. Robust pathway analysis over the 600 member ensemble of model-based generated scenarios. Each subplot compares the robustness of the stakeholders' negotiated pathway, in orange, with the most robust pathway for each design indicator using different colors (i.e., the pathway that minimizes the regret due to performance degradation in 75% of plausible futures). The horizontal axis direction is adjusted so that the leftmost value corresponds to the most desirable score for the considered indicator (i.e., the highest value for Hydropower and the lowest for Environment, Recession Agriculture, Fish, and Irrigation).

projected socio-economic and climatic conditions. The shape of the ECDF denotes the robustness of the performance against future uncertainties. Convex ECDFs (e.g., Hydropower, Recession, Irrigation) are associated with large vulnerabilities, where a small increase in performance on the x-axis implies a large drop on the y-axis in the percentage of futures under which that performance level is attained or exceeded. Conversely, sigmoidal shapes (e.g., Fish, Environment) indicate the presence of a tipping point in future conditions that turns the performance from robust to vulnerable.

In Fig. 5 we highlight the ECDF of the stakeholders' negotiated pathway (orange line) and the most robust pathways for the different indicators using different colors. For each indicator, the most robust pathway is defined as the one resulting in the minimum performance degradation with respect to the stakeholders' negotiated pathway in 75% of the considered futures. In other words, the robust pathway is the one that, for a large number of futures, minimizes the regret associated with a projected performance degradation. The 75% threshold was selected as a compromise between a risk-neutral approach, which would have searched for a minimum regret over 50% of future scenarios, and a completely risk-averse behavior, which would have searched a minimum regret over 100% scenarios. As visible from the figure, for a given indicator, the robust pathway is the uppermost solution in correspondence to the 75% tick on the vertical axis (marked with a dashed black line).

To further investigate the difference between the robust and stakeholders' negotiated pathways introduced in Fig. 5, we contrast the cyclostationary trajectories of Gibe III and Koysha levels simulated over the historical horizon (2002–2016). This comparative analysis can support the identification of good practices in reservoir operation that are expected to be robust against a broad range of future conditions. Results in Fig. 6 show that reservoirs levels should be kept fairly low to ensure robust performance in terms of recession agriculture and fish in Lake Turkana, allowing a recharge period between May to August to accumulate water which is released during the following months of September and October. The robust strategy, according to the other indicators, instead maintains the Koysha level high and close to the maximum operating level (upper black dashed line) for all pathways, while the Gibe III reservoir is variable.

4.3. Scenario discovery

In this section, we present the results of the scenario discovery analysis conducted via the Patient Rule Induction Method with the aim of identifying the most critical conditions under which the system is expected to fail. For this analysis, we focus on the stakeholders' negotiated pathway (bold line in Fig. 4), which was simulated over the 15,000 members ensemble of synthetically generated scenarios (see Section 3.3). Each of these scenarios is then characterized in terms of relative deviations in average, low (10th percentile), and high (90th percentile) streamflow magnitude with respect to the historical conditions. Moreover, changes in the northern (upstream Gibe III) and southern (downstream Gibe III) parts of the basin are considered separately to include a spatial dimension in the analysis. Finally, deviations in the water demands for both the Kuraz sugar plantation and the Private agricultural district are also included. The PRIM analysis was carried out independently for each design indicator, setting a failure threshold equal to the 25th percentile of the simulated future performance. Here we report the results related to Hydropower and Environment, as representative of the two antagonist interests in the system (see Fig. 4). It is worth mentioning that PRIM produces a set of results trading off Coverage and Density; here, we report the results obtained by choosing the knee point of the Pareto Front traced by Coverage and Density.

The scenario discovery results are illustrated in Fig. 7 as a scatterplot mapping each future scenario as a point in a bidimensional space, where red points indicate failures (i.e., the performance of the pathway is below the failure threshold) and blue points indicate successes (i.e., the performance of the pathway exceeds the failure threshold). The axes of the scatterplot are the most relevant drivers of future performance identified by the PRIM algorithm: deviations in the average and high flows in the northern part of the basin are selected as the most important drivers for Hydropower production, as they determine the water volumes entering the cascade of dams; for the Environment indicator, our results suggest the failure conditions will be primarily driven by alterations in both the northern and southern sub-basins. The black box superimposed on the scatterplots delimits the critical range of values of the two drivers that consistently corresponds to a failure. Interestingly, the results related to Hydropower (left panel) show that while the critical deviations in average flows (x-axis) are all negative (i.e., from 10% to 65% reductions), in the case of changes in high flow (y-axis), the system is expected to fail also under slightly positive deviations which are likely related to the frequent occurrence of dam spillages. The results for the Environment indicator (right panel) show that the relevant drivers of change are the deviations in the average streamflow in the northern (Δnorth_avg) and southern (Δsouth_avg) sub-basins, with the critical changes that are different for the two drivers. Not surprisingly, flow reductions in both the northern and southern sub-basins are considered critical as they will reduce most

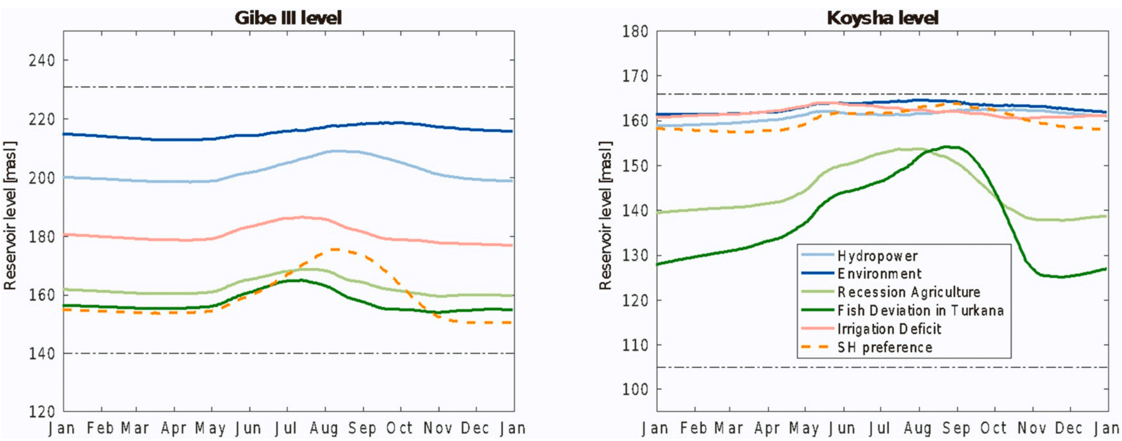


Fig. 6. Comparison of cyclostationary trajectories of Gibe III (left panel) and Koysha (right panel) levels for robust and stakeholders' negotiated pathway.

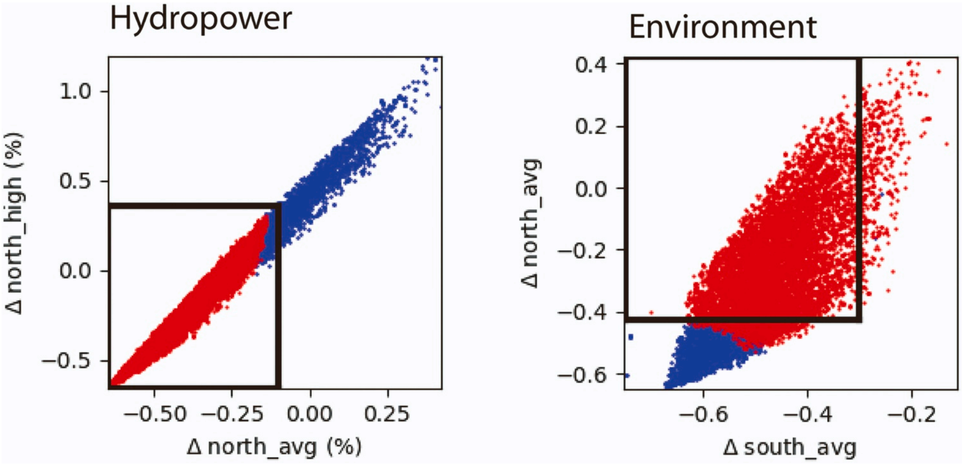


Fig. 7. Results of the scenario discovery via PRIM for the Hydropower (left panel) and Environment (right panel) indicators. Red pints identify scenarios classified as failures while blue points indicate success. The black box superimposed on the scatterplots delimits the critical range of values of the two drivers reported on the axes that consistently corresponds to a failure.

of the natural contribution to the flow in the delta not captured by the reservoirs. In addition, PRIM considers an increase in the average flow in the northern part of the basin as potentially critical for the Environment. This result may be explained by the fact that increasing inflows to Gibe III and Koysha reservoirs can result in a more frequent activation of the spillways that produce large and sudden water releases downstream, which can be highly disturbing for the ecosystems adapted to the natural hydrology.

5. Discussion

Our results discover more than 800 alternative strategies for operating the system that differently reconcile the competing water demands and uses in the OTB. The trade-off analysis conducted over these solutions shows that Hydropower and Irrigation are not particularly conflicting, which suggests that, similarly to other African systems (Giuliani et al., 2022; Alexander et al., 2020; Basheer et al., 2021), the dams and irrigation schemes are well designed from the perspective of these primary water uses. The sharpest conflict emerges between irrigation supply and fish production in Lake Turkana, emphasizing the transboundary issue of the basin as the irrigated areas are in Ethiopia, whereas the majority of Lake Turkana is in Kenya. This finding is in line with the results from Avery and Tebbs (2018), which emphasizes the risks for Lake Turkana induced by large water abstractions for irrigation supply.

Interestingly, the stakeholders' negotiated pathway indicates a slight preference for Fish at the expense of Irrigation. Our interpretation of this result is related to the fact that large scale irrigation is something that, in the context of our analysis, does not exist yet, so every solution is somehow better than the historical situation, while other sectors like Fish or Environment have their historical reference negatively impacted by the majority of the considered pathways. This pathway indeed attains a performance in the top 20% of the solutions' set for Environment, Recession, and Fish, primarily at the cost of a performance in terms of irrigation deficit close to 45% of best feasible solution, along with a 70 GWh/y reduction in hydropower production. This result is not surprising as a good performance in terms of Environment, Recession, and Fish requires a streamflow regime close to the natural conditions in the lower Omo, which can be obtained by limiting the water diversion, especially to the Kuraz sugar plantation. The practical implementation of this solution would entail reducing the extent of the irrigation district or increasing the fraction of fallow land within the district, a recommendation that is similar to the ones suggested by Hodbod et al. (2019). The possibility of implementing this pathway is, however, controversial as the original investments described in the Master Plan were largely motivated by the expansion of hydropower and irrigated agriculture. Additional efforts are likely needed to identify an implementable solution with a better performance in terms of Hydropower and Irrigation, possibly introducing additional mitigation options for reducing the negative impacts of this alternative solution on the other stakeholders. The fact that the NSL was clearly framed as a simulation exercise, likely encouraged participants to explore solutions with low political acceptability but potentially interesting. Some stakeholders indicate that a possible way to resolve the strong trade-off between Irrigation and Fish can be favoring the practices of aquaculture in the Omo delta to reduce the dependency on natural fish yields in Lake Turkana. In addition, increasing the access to small-scale irrigation pumps for the communities relying on flood recession agriculture can contribute to enhancing the acceptability of a more Hydropower-inclined solution. Further studies are however needed to assess the social implications of these interventions for the pastoralist communities living the lower Omo Valley (Amos et al., 2021).

The second part of our analysis shows that the performance of the considered pathways is expected to degrade under the considered ensemble of future scenarios, with large vulnerabilities in terms of hydropower production, recession agriculture, and water supply for irrigation. The scenario discovery performed over a larger ensemble of 15,000 synthetically generated scenarios provides valuable insights about the main sources of vulnerability of the system: changes in streamflow in the northern basin emerge as the most critical for the system as a whole, while reductions in streamflow in the south of the basin are generally less relevant probably because they carry much lower volumes of water compared to the northern flows. Over the next years, stakeholders and decision-makers should therefore carefully monitor the evolution of the upper part of the basin, particularly with respect to the existing projects for expanding small-scale irrigated agriculture in that area (Avery and Tebbs, 2018) which could substantially decrease the water volumes flowing into the southern part of the basin.

A limitation in the presented results is the simplified representation of some key hydrological processes in the Omo River delta, particularly in terms of evaporation losses occurring when floodwater spreads over the floodplain or flow returns from the irrigated areas. These simplifications influence the simulated water balance in the delta with respect to the role of irrigation abstractions against the evaporation losses in natural conditions. However, we expect return flow to play a minor role because the irrigation policy is designed to meet the irrigation demands required for optimal agricultural yield. Another simplification of our model is related to the use of average travel times along the river stretches, impacting the assessment of both environment and recession agriculture. All these assumptions have been resolved in the DAFNE project, which also produced a high-fidelity assessment of selected pathways obtained by re-simulating them using the Topkapi-ETH model. Yet, the computational requirements of this model prevent its use in large Monte Carlo simulations and robustness analysis, ultimately making the above simplifications unavoidable for the present study. Furthermore, our results do not account for the dams' contribution related to flood protection as this aspect was not raised by our stakeholders during the NSL dedicated to the definition of assessment indicators. It is worth remarking that, while dams designed for flood protection typically include a flood buffer zone, this latter is not present in either Gibe III or Koysha, thus suggesting this aspect is likely secondary with respect to the role of hydropower production.

6. Conclusions

In this paper, we describe the implementation of a participatory decision-analytic framework for promoting water-related development pathways that are efficient, socially inclusive, and environmentally sustainable. The application of this approach in the Omo-Turkana Basin enabled the exploration of multisectoral trade-offs across the main stakeholders impacted by the ongoing hydropower and agricultural expansion projects in the basin, including indigenous recession agriculture, ecosystem services in the Lower Omo, and fish yield in Lake Turkana. Moreover, we assessed the robustness of these alternative development pathways across a broad array of plausible climate and socio-economic futures.

Overall, the pathway negotiated by the stakeholders during the Negotiation Simulation Labs represents a good compromise across all competing interests with relevant degradation of performance only for irrigated agriculture. Moreover, it attains a medium level of robustness when exposed to the uncertainty of future scenarios. This solution, which recommends keeping a large buffer in Gibe III to handle the future inflow variability while keeping Koysha close to its full supply level (see Fig. 6), emerges as a promising balanced solution to address the multisectoral trade-offs across multiple uncertain futures.

These findings suggest that our participatory decision-analytic framework provides stakeholders and decision-makers with a rich context for better understanding complex multisector dynamics and for prioritizing investments in projects. The extensive trade-off analysis investigating alternative operations of the system suggests there is space for enhancing the flexibility and the adaptive capacity of the basin without the need for additional infrastructural upgrades and associated financial outlays. Finally, our results show how facilitating the negotiation of compromise solutions balancing diverse and competing indicators could contribute to increasing the system resilience under changing climate and society. To ensure the correct interpretation of the simulated outputs and a common understanding across all stakeholder groups, we recommend planning dedicated training sessions to acquire the necessary competencies.

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Code availability

Available under request. A public repository will be published upon acceptance of the paper.

CRediT authorship contribution statement

M.G.: Methodology, Software, Investigation, Writing – original draft, Visualization, Supervision. **M.Z.**: Software, Formal analysis, Investigation, Writing – original draft, Visualization. **S.S.**: Formal analysis, Investigation, Writing – review & editing. **M.M.**: Investigation, Data curation. **J.V.O.**: Writing – review & editing, Funding acquisition. **P.B.**: Writing – review & editing, Funding acquisition; **A.C.**: Methodology, Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All raw data used in this manuscript are freely available at the following websites: historical temperature (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/); historical precipitation (https://www.tamsat.org.uk/); climate projections (http://www.csag.uct.ac.za/cordex-africa/).

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Declarations competing interests

The authors declare no competing interests.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101116.

References

AfDB, 2020. The African Development Bank Groups New Draft Policy on Water. African Development Bank Group, s.l.
Alexander, S., Wang, G., Addisu, G., Block, P., 2020. Forecast-informed reservoir operations to guide hydropower and agriculture allocations in the Blue Nile Basin, Ethiopia. Int. J. Water Resour. Dev. 1–26.
Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and drainage paper, Rome, Italy.
Amos, S., Mengistu, S., Kleinschroth, F., 2021. Three decades of pastoralist settlement dynamics in the Ethiopian Omo Delta based on remote sensing data. Hum. Ecol. 49, 525–537.
Avery, S., 2013. What future for Lake Turkana? The Impact of Hydropower and Irrigation Development on the World's Large Desert Lake. African Studies Centre, University of Oxford, Oxford, UK.
Avery, S., Eng, C., 2012. Lake Turkana & the Lower Omo: Hydrological Impacts of Major Dam and Irrigation Developments. African Studies Centre, the University of Oxford, Oxford UK.
Avery, S., Tebbs, E., 2018. Lake Turkana, major Omo River developments, associated hydrological cycle change and consequent lake physical and ecological change. J. Gt. Lakes Res. 44 (6), 1164–1182.
Basheer, M., et al., 2021. Collaborative management of the Grand Ethiopian Renaissance Dam increases economic benefits and resilience. Nat. Commun. 1.
Bertoni, F., Castelletti, A., Giuliani, M., Reed, P., 2019. Discovering dependencies, trade-offs, and robustness in joint dam design and operation: an ex-post assessment of the Kariba dam. Earth's Future 7, 1367–1390.
Brouwer, C., Prins, K., Heibloem, M., 1989. Irrigation Water Management – Training Manual No. 4 – Irrigation Scheduling. United Nations Food and Agriculture Organisation, Rome, Italy.
Bryant, B., Lempert, R., 2010. Thinking inside the box: a participatory, computer-assisted approach to scenario discovery. Technol. Forecast. Soc. Change 77 (1), 34–49.
Castelletti, A., Pianosi, F., Soncini-Sessa, R., 2008. Water reservoir control under economic, social and environmental constraints. Automatica 44 (6), 1595–1607.
Castelletti, A., Soncini-Sessa, R., 2006. A procedural approach to strengthening integration and paticipation in water resource planning. Environ. Model. Softw. 21 (10), 1455–1470.
Celeste, A., Billib, M., 2009. Evaluation of stochastic reservoir operation optimization models. Adv. Water Resour. 32 (9), 1429–1443.
Cretaux, J., et al., 2011. SOLS: a lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. Adv. Space Res. 47 (9), 1497–1507.
EEPCO, 2009. Environmental and Social Impact Assessment. Ethiopian Electric Power Corporation, s.l.
Fatichi, S., et al., 2016. An overview of current applications, challenges, and future trends in distributed process-based models in hydrology. J. Hydrol. 537, 45–60.
Friedman, J., Fisher, N., 1999. Bump hunting in high-dimensional data. Stat. Comput. 9 (2), 123–143.
Gibson, J., Yihdego, Z., 2021. Pathways to enhanced cooperation. In: Lautze, J., McCartney, M., Gibson, J. (Eds.), The Omo-Turkana Basin. Cooperation for Sustainable Water Management. Routledge, London.
Giuliani, M., et al., 2016. Curses, tradeoffs, and scalable management: advancing evolutionary multi-objective direct policy search to improve water reservoir operations. J. Water Resour. Plan. Manag. 142, 2.
Giuliani, M., Herman, J., Castelletti, A., Reed, P., 2014. Many-objective reservoir policy identification and refinement to reduce policy inertia and myopia in water management. Water Resour. Res. 50, 3355–3377.
Giuliani, M., et al., 2022. Unintended consequences of climate change mitigation for African river basins. Nat. Clim. Change 12.
Giuliani, M., Lamontagne, J., Reed, P., Castelletti, A., 2021. A state- of-the-art review of optimal reservoir control for managing conflicting demands in a changing world. Water Resour. Res. 57, e2021WR029927.
Giuliani, M., et al., 2018. Scalable multiobjective control for large-scale water resources systems under uncertainty. IEEE Trans. Control Syst. Technol. 26 (4), 1492–1499.
Gownaris, N., et al., 2017. Fisheries and water level fluctuations in the world's largest desert lake. Ecohydrology 10, 1.
Haasnoot, M., et al., 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. Clim. Change 115 (3–4), 795–819.
Hadka, D., Reed, P., 2013. Borg: an auto-adaptive many-objective evolutionary computing framework. Evolut. Comput. 21 (2), 231–259.
Herman, J., et al., 2020. Climate adaptation as a control problem: review and perspectives on dynamic water resources planning under uncertainty. Water Resour. Res. 56.
Herman, J., Reed, P., Zeff, H., Characklis, G., 2015. How should robustness be defined for water systems planning under change? J. Water Resour. Plan. Manag.
Hermans, L., 2005. Actor Analysis for Water Resources Management: Putting the Promise Into Practice. Eburon Uitgeverij BV, s.l.
Hodbod, J., et al., 2019. Social-ecological change in the Omo-Turkana basin: a synthesis of current developments. Ambio 48, 1099–1115.

Huffman, G., et al., 2007. The TRMM multi-satellite precipitation analysis: quasi-global, multi-year, combined-sensor precipitation estimates at fine scale. J. Hydrometeorol. 8, 1.
IISD, 2019. IEA Report Presents Scenarios for Sustainable Energy, SDG 7 Outlook for Africa. International Institute for Sustainable Development, s.l.
International Energy Agency, 2019. Ethiopia Energy Outlook. IEA, Paris.
Jeuland, M., Whittington, D., 2014. Water resources planning under climate change: assessing the robustness of real options for the Blue Nile. Water Resour. Res. 50 (3), 2086–2107.
Kleinschroth, F., et al., 2021. Narratives underlying research in African river basin management. Sustain. Sci. 16, 1859–1874.
Liu, Z., Todini, E., 2002. Towards a comprehensive physically-based rainfall-runoff model. Hydrol. Earth Syst. Sci. 6 (5), 859–881.
Lumosi, C., 2020. Shaping Transboundary Water Governance – How Learning Spaces Shape Transboundary River Basin Management Practices and Processes in the Omo-Turkana and Zambezi River Basins (Ph.D. Dissertation). s.l.
Matalas, N., Fiering, M., 1977. Water-resource systems planning. In: Climate, Climatic Change, and Water Supply, Studies in Geophysics. National Academy of Sciences, Washington, DC, pp. 99–110.
McPhail, C., et al., 2018. Robustness metrics: how are they calculated, when should they be used and why do they give different results? Earth's Future 6.
Melenhorst, M. , et al., 2018. NSL Technical Implementation Plan. s.n., s.l.
Moss, R., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282), 747–756.
OECD, 2017. Multi-Purpose Water Infrastructure: Recommendations to Maximize Economic Benefits. s.n., s.l.
Peleg, N., et al., 2017. An advanced stochastic weather generator for simulating 2-D high-resolution climate variables. J. Adv. Model. Earth Syst. 9, 1595–1627.
Peleg, N., Molnar, P., Burlando, P., Fatichi, S., 2019. Exploring stochastic climate uncertainty in space and time using a gridded hourly weather generator. J. Hydrol. 571, 627–641.
Priestley, C., Taylor, R., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev. 100, 81–92.
Quinn, J., et al., 2018. Exploring how changing monsoonal dynamics and human pressures challenge multireservoir management for flood protection, hydropower production, and agricultural water supply. Water Resour. Res. 54 (7), 4638–4662.
Reichle, R., et al., 2017. Land surface precipitation in MERRA-2. J. Clim. 30, 5.
Soncini-Sessa, R., Castelletti, A., Weber, E., 2007. Integrated and Participatory Water Resources Management: Theory. Elsevier, Amsterdam.
Steduto, P., Hsiao, T., Raes, D., Fereres, E., 2009. AquaCrop-the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101 (3), 426–437.
The Economist, 2016. Ethiopia opens Africa's tallest and most controversial dam. December.
Trindade, B., et al., 2017. Reducing regional drought vulnerabilities and multi-city robustness conflicts using many-objective optimization under deep uncertainty. Adv. Water Resour. 104, 195–209.
UNESCO-UN-Water, 2020. United Nations World Water Development Report 2020: Water and Climate Change. UNESCO, Paris.
Warner, J.J.S., Jones, E., Ansari, M., De Vries, L., 2019. The fantasy of the Grand Inga Hydroelectric project on the River Congo. Water 11 (3), 407.
webuild, 2018. Clean Hydro-Energy. [Online] Available at: ⟨https://www.webuildgroup.com/it/progetti/clean-hydro-energy⟩, (Accessed 02 2018).
Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65 (7), 180–185.
Woodroofe, R., 1996. Omo-gibe River Basin Integrated Development Master Plan Study Final Report, VI. Water resources Surveys and Inventories, Ministry of Water Resources, Addis Ababa.
Zaniolo, M., Giuliani, M., Bantider, A., Castelletti, A., 2021a. Hydropower development. Economic and environmental benefits and risks. In: Lautze, L., McCartney, M., Gibson, J. (Eds.), The Omo-Turkana Basin. Cooperation for Sustainable Water Management. Routledge, London.
Zaniolo, M., et al., 2021b. When timing matters-misdesigned dam filling impacts hydropower sustainability. Nat. Commun. 12.
Zatarain-Salazar, J., et al., 2016. A diagnostic assessment of evolutionary algorithms for multi-objective surface water reservoir control. Adv. Water Resour. 92, 172–185.