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Key Points:
- System wide multi-sector assessments reveal the benefits of coordinated interventions and help identify sectoral trade-offs
- Trade-offs between water, energy, food and environment can be optimised under different scenarios of river basin development
- Multi-criteria decision-making methods can inform collaborative water-energy-food-environment system planning in Tanzania

Supporting Information:
- Supporting Information S1

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Assessing River Basin Development Given Water-Energy-Food-Environment Interdependencies

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Abstract Many river basins in the Global South are undergoing rapid development with major implications for the interdependent water-energy-food-environmental (WEFE) "nexus" sectors. A range of views on the extent to which such natural-human systems should be developed typically exists. The perceived best investments in river basins depend on how one frames the planning problem. Therefore, we propose an approach where the best possible (optimized) implementations of different river basin development scenarios are assessed by comparing their WEFE sector trade-offs. We apply the approach to Tanzania's Rufiji river basin, an area with multiple WEFE interdependencies and high development potential (irrigation and hydropower) and ecosystem services. Performance indicators are identified through stakeholder consultation and describe WEFE sector response under scenarios of river basin development. Results show considerable potential exists for energy and irrigation expansion. Designs that prioritize energy production adversely affect environmental performance; however, part of the negative impacts can be minimized through release rules designed to replicate the natural variability of flow. The reliability of monthly energy generation is more sensitive to environmental-oriented management than the cumulative annual energy production. Overall results highlight how sectoral trade-offs change depending on the extent of development, something that may be difficult to regulate in the future, and that there are important basin-scale interdependencies. Benefits and limitations of the approach and its application are discussed.

Plain Language Summary Infrastructure in water-energy-food-environment systems such as dams can play a beneficial role in supporting hydropower production and regulating the variability of river flow. However, these benefits often come with negative environmental impacts on wildlife, affect income from other economic sectors, and can damage river-linked ecosystems (e.g., wetlands, floodplains, riverine forests, and mangroves). System-scale option assessment approaches that consider the different relevant issues simultaneously help identify infrastructure and operating policy designs with acceptable balances of potential benefits and impacts. While optimized model-based assessments can balance outcomes across performance metrics, this is contingent on the need for effective coordination between sectors and between upstream-downstream developments. One way to help design future systems is to compare the energy, agricultural, and environmental conservation trade-offs implied by different extents of development (i.e., realization of various reservoirs and irrigation schemes). We apply such a multisector spatial computer-aided design approach to the Rufiji river basin in Tanzania and consider linkages across the water-energy-food-environment sectors. Results show considerable potential for infrastructure development in the basin but highlight important trade-offs between the sectors, particularly how downstream performance indicators are affected by upstream cumulative effects of informal irrigation expansion, something that may be difficult to regulate in the future.

1. Introduction

Many river basins in the Global South are undergoing rapid development through the planned and unplanned actions of governments, corporations, and small-scale agents, ostensibly to meet growing demand for agricultural and energy production. Investment choices can be complicated by conflicting river basin goals including, for example, increasing the amount and reliability of hydropower generating capacity, water supply for urban and irrigation expansion, and minimizing costs and environmental harm (Connor et al., 2015).

A multisector, multicriteria system-scale approach allows exploring interdependencies across multiple indicators and multiple water-energy-food-environment (WEFE) sectors (Albrecht et al., 2018; Chang et al., 2016), helping address low representation and access to information for marginalized stakeholder groups in basin-wide plans (Lele et al., 2013). System-wide basin-scale assessments help identify investment portfolios that synergistically maximize benefits and minimize negative impacts that occur through interdependencies (Cosgrove & Loucks, 2015). However, while strong interdependencies exist across critical sectors such as water, energy, food, and environment (the WEFE “nexus”), attempts to quantify multidimensional synergies and trade-offs in real-world nexus systems are still rare (Albrecht et al., 2018; Liu et al., 2017).

While the case for adopting an integrated perspective is strong and has been widely promoted, institutional and governance aspects of nexus integration have received less attention despite being relevant to both analysis and implementation (Albrecht et al., 2018; Bai & Sarkis, 2019; Leck et al., 2015). Various frameworks have been advanced to address governance challenges resulting from the alternative narratives and logics that exist in different nexus sectors. These include a network and ecosystem services framing (Pahl-Wostl, 2019); a dual holistic integration framework and vertical policy integration approach used jointly to span a spectrum of integration options (Märker et al., 2018); identifying entry points and institutional levels that account for differences and diversity in actors' viewpoints (Kurian, 2017); and identifying responsibilities for management and regulation (Johnson & Karlberg, 2017). A question posed in the literature is whether new organizations should be created to manage the nexus (Johnson & Karlberg, 2017; Keskinen et al., 2016), with some calling for building institutional capacities (Bazilian et al., 2011; Kaddoura & El Khatib, 2017; Kurian, 2017) and better coordination (Helmstedt et al., 2018) and others for new institutional arrangements for implementing the nexus (Al-Saidi & Elagib, 2017).

Allouche et al. (2019) emphasize the need to recognize that nexus approaches are political processes, not just procedurally technical ones, requiring negotiation between different actors with contrasting views, priorities, and practices. Recognizing this includes acknowledging the existence of unequal distribution of power, agency, and access to information and resources (Lele et al., 2013; Mercure et al., 2019). Power imbalances and competition between sectors also act at the institutional level, leading to siloed approaches and suboptimal solutions with institutions often following their own agenda and seeking to preserve their influence (Cai et al., 2018). The gaps between provision of robust and legitimate information and effective decision-making and implementation are known (e.g., Kurian, 2017), if not always acknowledged.

Approaches that identify benefits and trade-offs and enable their deliberation with diverse stakeholder groups can help make river basin intervention decisions more transparent and sustainable (Social Council & United Nations, 2008). The availability of new multicriteria simulation-optimization-based design methods (Geressu & Harou, 2015; Giuliani et al., 2014; Hadka & Reed, 2013), interactive visualization, and the recognition of the need for co-design (Grainger et al., 2016; Inselberg, 2009; Kollat & Reed, 2007; Woodruff et al., 2013) could help enable strategic model-assisted river basin development planning (Hoff, 2011; Hurford, McCartney, et al., 2020; Leck et al., 2015). Quinn et al. (2017) show that different quantitative representations of the system's objectives change the recommendations of a system planning using multiobjective optimization. Their demonstration that interrogating competing hypotheses of how complex resource management problems are formulated leads to greater understanding and better model-based decision support and seems appropriate to nexus systems.

In this paper, we propose and apply a multisector multiobjective optimized WEFE system design approach to strategic river basin planning. Inspired by Quinn et al. (2017), we seek to compare different extents of river basin development by assessing for each the performance of different sectors and their trade-offs. To this end, we formulate different “development scenarios” implementing progressively more interventions. The approach shows how future and existing development options might impact each other's performance and reveals system interdependencies as the number of interventions grows. We also explore how differing assumptions about approaches to irrigation water management (resulting in different irrigation return flow rates [IRFRs]) and the size of a large planned dam affect trade-offs and performance metrics. We use visual analytics (Woodruff et al., 2013) to help identify balanced design alternatives from among a large pool of equally efficient (Pareto-optimal) options.

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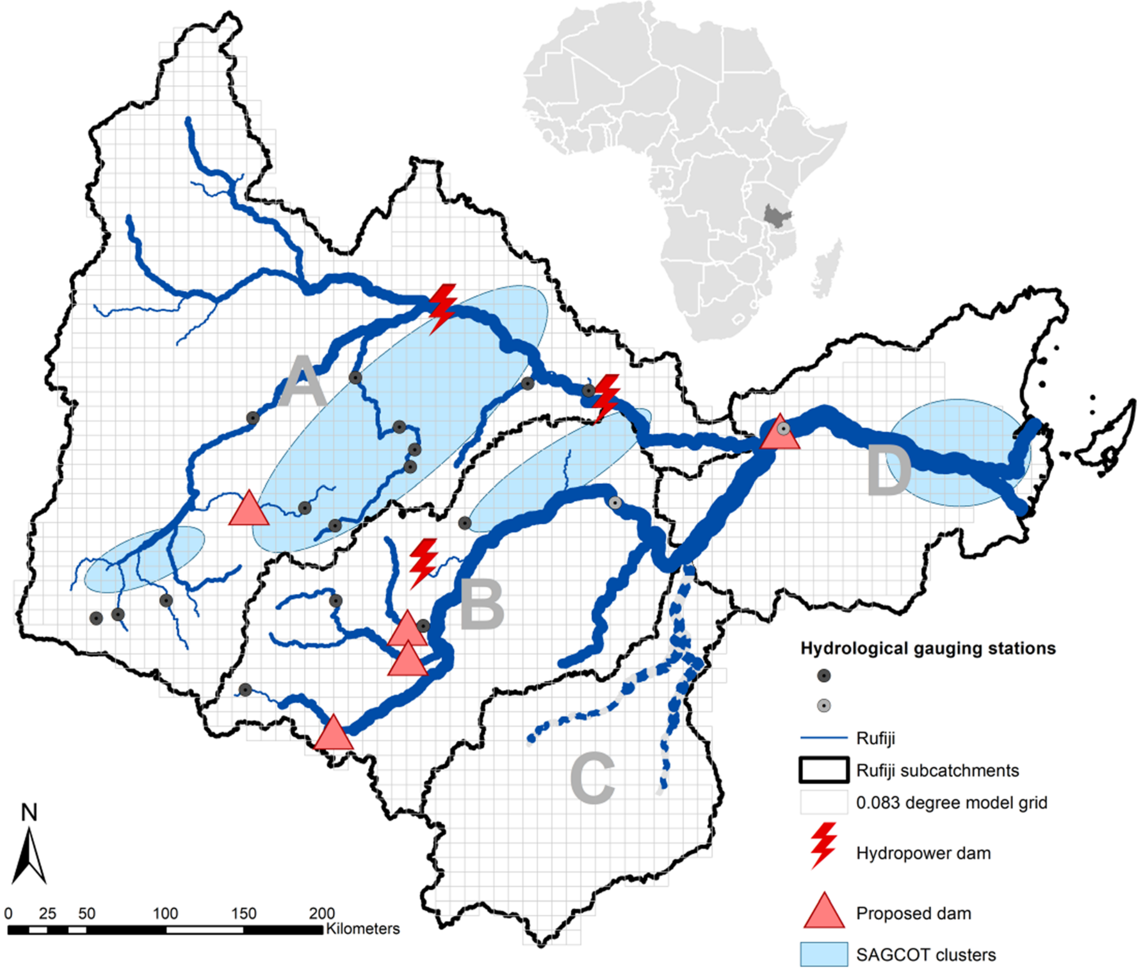

Figure 1. The Rufiji basin, hydrological model resolution (grids), subcatchments (A, Great Ruaha; B, Kilombero; C, Luwegu; and D, Lower Rufiji River), flow gauging stations, four SAGCOT clusters, and existing hydropower dams and proposed dams.

We demonstrate the approach's applicability by examining the WEFE implications of development options in Tanzania's Rufiji river basin. Section 2 explains the resource planning and management challenge of the Rufiji system. Section 3 describes simulation and optimization methods deployed and their application to the Rufiji case study. Performance metrics for evaluating interventions selected through consultation with stakeholders and water resources system experts are described. Section 4 describes how the proposed approach was applied to the Rufiji. Section 5 presents results and explores performance trade-offs in energy generation, agricultural water supply, and environmental flows in four "development scenarios." A discussion of results, assumptions, and limitations of the study is presented in section 6, followed by conclusions in section 7.

2. Rufiji River Basin

The Rufiji river basin, Tanzania's largest, supplies water for around 4.5 million people and generates 80% of Tanzania's hydropower and covers roughly 20% of the country (177,420 km^2, Figure 1). Much of the basin is targeted by the government for socioeconomic development over the next two decades as part of the Southern Agricultural Growth Corridor of Tanzania (SAGCOT) (Paul & Steinbrecher, 2013). The SAGCOT comprises several concentrated areas of activity (clusters), and it aims to attract domestic and foreign investment in agricultural value chains to promote economic growth (Isaac & Guyver, 2011; Milder et al., 2012). Increased agricultural productivity, particularly through increased irrigation, is part of the initiative, and sustainable water resource management is viewed as key to its success. The basin is estimated to have 2 million hectares (ha) of medium- to high-potential irrigable land, with 4.5% currently under irrigation. An estimated 2.4 billion cubic meters of water (BCM) is currently abstracted per year, primarily for irrigation, and this is projected to increase to 7.6 BCM per year to support expansion of irrigation from 110,000 to 400,000 ha by 2035 (WREM International Inc., 2015).

Planned irrigation in the Rufiji river basin is set and managed by the National Irrigation Commission under the framing of the National Irrigation Masterplan and supported by aid-funded feasibility studies. Autonomous irrigation development by smallholder farmers is a land use change driver where practical policy influence is more uncertain (informant interview, 2019) and is currently expanding in the wetlands of the Kilombero subcatchment (Figure 1), the largest contributor to the Rufiji main stream flows (informant interview, 2019). In practice, enforcement of village land use plans, framed by Village Land Use Plans drawn by the Ministry of Lands, Housing and Human settlements, is weak and poorly coordinated between the district and village levels, and wet season expansion has been estimated to now cover one to two thirds of the wetlands (informant interview, 2019). The Water Act of 2009 enshrines into law formal water management in Tanzania, and the water allocation is managed by the Rufiji Basin Water Board (in the Ministry of Water) but has limited capacity to enforce regulation of water permits. Any water abstraction without a permit is defined as illegal and customary rights are not recognized, but in practice, many smallholder farmers abstract with no permit (informant interview, 2019). Water user associations (WUAs) are to support the formalization of water access for smallholder farmers but have so far led to mixed results as the poorest have been found to leave some farmers behind (Richards, 2019). While the extent of informal irrigation expansion alongside the planned schemes in the future is unclear, it is an ongoing process.

The efficiency of irrigation determines the amount of return flows. In effectively managed schemes, drainage systems capture excess water and reroute it back to the main river. In the Rufiji river basin, current practice is rather different. Irrigated agriculture in the basin consists of centrally controlled irrigation schemes surrounded by informal irrigation by smallholders, who capture and reuse irrigation return flows locally responding in part to the interannual variability in water availability (Lankford & Beale, 2007). While this increases local production and local system efficiency, less return flow reaches downstream to be used again for irrigation or hydropower production. We have therefore assumed a baseline situation in which only soil drainage but no canal conveyance losses are returned to the river. Based on the hydrological model, an average IRFR of 35% was derived. In the future, land use and water abstractions of smallholders might be managed more effectively to preserve some return flows. To represent this, simulated canal conveyance losses are added to return flows, and instead of 35%, 55% of irrigation water is returned to the river (IRFR of 55%) (supporting information [SI] section S1).

Several new dams and run-of-river hydropower plants are planned. A major recent development has been the decision in 2017 to go ahead with the Julius Nyerere Hydropower Project (JNHP) at Stiegler's gorge on the Rufiji mainstem (Figure 1). The JNHP was first conceived in the 1950s (Hoag & Öhman, 2008) and revisited in the mid-2000s as a flagship project to support the country's growth and economic transition agenda while responding to the country's energy crisis (WWF, 2018). In 2019, budget to begin construction has reportedly been assigned (Mulyungi, 2019), attracting international criticism from conservation organizations (WWF, 2018). The widely quoted reservoir area (1,200 km^2) in the current design of 32 BCM capacity would flood roughly 2% of the 50,000 km^2 Nyerere National Park (formerly Selous game reserve), a UNESCO World Heritage site since 1982 (UNESCO, 2014). The dam, depending on the reservoir management mode (e.g., if operated for a constant flow regime), could transform the functions of the downstream floodplain and delta of the Lower Rufiji River (Duvail et al., 2014; Shaghude, 2016; WWF, 2018).

Various studies (Duvail et al., 2014; Isaac & Guyver, 2011; Shaghude, 2016) have investigated discrete aspects of the financial, environmental, and socioeconomic issues associated with proposed projects in the basin, but there have been few basin-wide strategic studies. One basin-scale study was conducted to support the Rufiji Basin Water Board in their planning of water demand for hydropower and agriculture (WREM International Inc., 2015). However, analysis that reveals the interdependencies and potential trade-offs that could occur across the WEFE sectors is lacking. This is a concern, given ongoing changes in the basin are already associated with important points of contestation (Materu et al., 2018). For example, at various times, tensions and competing explanations have played out in the Great Ruaha subcatchment over the actions and

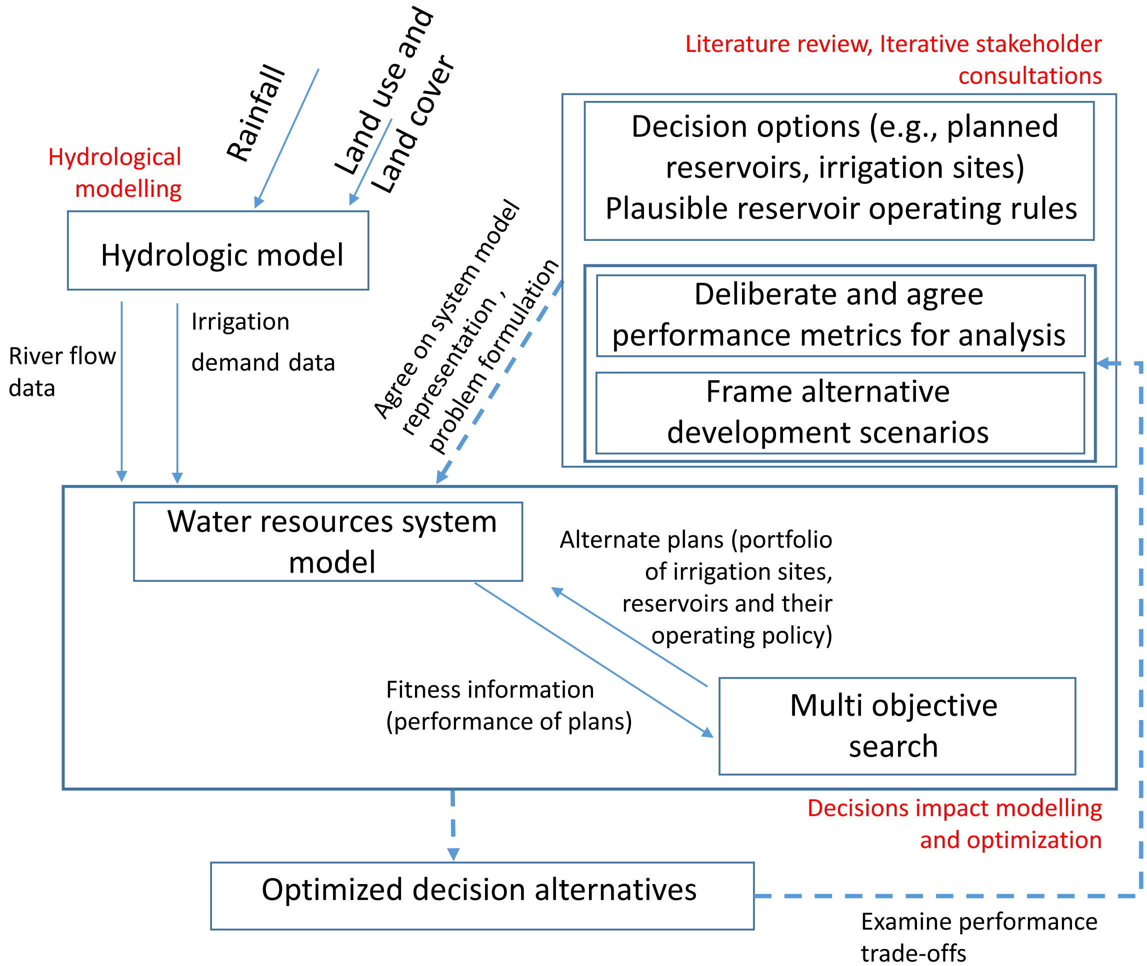

Figure 2. Overview of the linked models and data and decision inputs.

impacts of smallholder agriculture and pastoralists, irrigation expansion, land-grabbing, and conservation (England, 2019; International Work Group for Indigenous Affairs, 2018; Kashaigili et al., 2006; Lankford et al., 2009; Mwakalila, 2005; O'Keeffe et al., 2017; The Citizen, 2015; Walsh, 2012).

Cross-sectoral collaboration in the Rufiji, and in Tanzania in general, is limited due to siloed institutional structures (Pardoe et al., 2018). While we assume an ability to coordinate operating policies of existing and planned reservoirs and irrigation schemes in an effort to highlight the benefits of joined up strategic river basin planning, we review this assumption in the discussion. While WEFE-nexus-coordinated strategic planning may be ideal, the possibility of noncoordinated development such as the cumulative effects of irrigation expansion by individual smallholder farmers should be considered.

3. Methods

3.1. Systems Modeling

The proposed integrated suite of models, processes, and decisions is outlined in Figure 2. We use a hydrological model in combination with a water resources system model to simulate development scenarios in the basin. Hydrological modeling is used to transform rainfall into river flow time series and to evaluate agricultural water demands.

3.1.1. Hydrological Model

For our analysis, we used a local application of the global hydrological model LPJmL to simulate runoff, irrigation water demand, and irrigation return flows for the main Rufiji tributaries, for current and future plans

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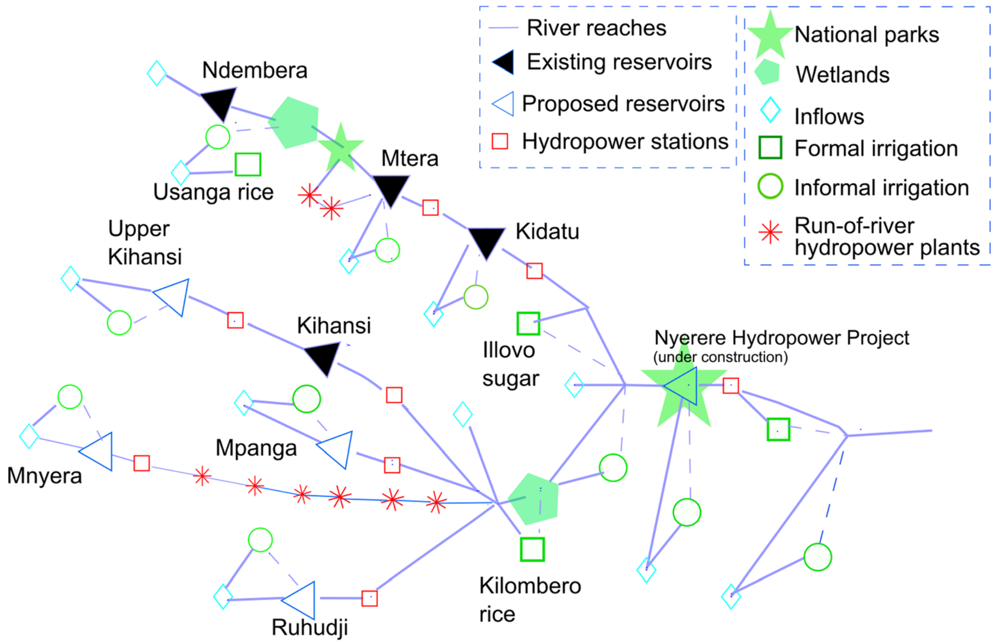

Figure 3. Water resources system management model schematic showing existing and planned Rufiji basin reservoirs (filled and hollow triangles, respectively), planned and informal irrigation expansion areas (squares and circles, respectively), and flow-augmenting wetlands.

for irrigation expansion (Siderius et al., 2018). Most hydrological modeling in the Rufiji has concentrated on the Great Ruaha subcatchment (Figure 1), aiming to explain the causes of declining dry season flows entering the Ruaha National Park during the late 1990s and 2000s (Walsh, 2012). The model of Siderius et al. (2018) runs at ~9 km resolution (Figure 1, further details in SI section S2) and is the first published model developed for the whole Rufiji river basin. Critical data requirements in a large sparsely monitored basin include information on wetland characteristics and in situ observations of rainfall and discharge at key sites throughout the basin. Nevertheless, after limited calibration, the model performed well in simulating average annual flows, monthly time series, and seasonal patterns and reasonably well in simulating observed interannual variability, with Kling-Gupta model Efficiency (KGE) values ranging from 0.59 to 0.82 for a range of smaller subcatchments (Siderius et al., 2018). The model was developed with the purpose of providing inputs to a water resource system management model.

3.1.2. Water Resources System Management Model

The water resources system management model is a classical node-link river basin simulator (Loucks et al., 1981, 2005) using a dendritic network structure to represent the conveyance systems (rivers, canals, etc.) connecting supply (e.g., river inflow nodes) and demand (where water generates benefits). Time series of river flows and irrigation water demand pass from the hydrological model to the water management model at inflow and water demand nodes, respectively. The management model represents both existing and planned irrigation sites and sites of ecological interest (water demand nodes) and large dams (storage nodes). The management model tracks various performance metrics (see section 3.2) such as energy generation and water supply reliability at different locations in the basin for a given combination of irrigation expansion and hydropower dam options (SI section S3). This study uses the generalized Interactive River-Aquifer model (IRAS-2010) (Matrosov et al., 2011).

The water resources system management model represents the Rufiji river basin including all the existing and government-planned irrigation sites and large dams. The system's topology (disposition and connectivity of supply and demand nodes) is shown in Figure 3; there are 11 irrigation demand nodes, four reservoirs (three of which are used for hydropower: Kidatu, Mtera, and Kihansi), and the Ndembera dam. The planned developments comprise five new reservoirs: the Julius Nyerere Hydropower Project, Ruhudgi, Mpenga, Upper Kihansi, and Mneyera, eight run-of-river hydropower dams, and four irrigation sites.

Table 1
List of Performance Metrics Included in the Analysis

Category	Performance metrics	Rationale and derivation
Energy	Total average annual energy from all dams in gigawatt hour per year (GWh/year)	Indicates potential energy generated from existing and new reservoirs in a typical year.
	Firm annual energy (GWh/year)	Calculated from the statistical distribution of the annual energy generation in a simulated period and indicates the amount that can be reliably generated (i.e., the level exceeded 99% of the time).
	Firm monthly energy (GWh/month)	The monthly energy generation that is exceeded 99% of the time. It is an indicator of how the energy generation is distributed seasonally and the reliability of energy supply.
Irrigation	Total irrigation area (hectares)	Sum of all areas that can be irrigated.
	Irrigation water supply demand deficit (MCM/year)	The sum of the unmet water demand of the irrigation areas. It indicates the extent to which the combination of assets leads to water supply deficits. This metric, along with the total irrigation area, is a proxy for the irrigated agriculture production in the basin for both local and national consumption.
Environmental metrics	Area flooded by the Julius Nyerere Hydropower Project reservoir (hectares)	The size of the Julius Nyerere Hydropower Project is fixed; however, as a sensitivity analysis, we evaluate the impact (on energy performance) of constraining the area flooded by the reservoir.
	Lower Rufiji flow disruption (unitless metric)	Change in hydrological variability due to upstream regulation just downstream of the location of the Julius Nyerere Hydropower Project (see SI section S6 for details).

The evaporation losses and the impact of regulating river flow from the Usangu and Kilombero wetlands is represented by modeling the wetlands as reservoirs. The system network is represented with four confluence nodes and 71 links representing river reaches (Figure 3). This setup draws from basin planning reports including the latest river basin management plan (WREM International Inc., 2015).

3.1.3. Multiobjective Optimization

Connecting the water resources system management simulation model to a multiobjective search enables a trade-off analysis between the most efficient development combinations (see Figure 2). The automated multiobjective search process seeks to find which combinations of interventions (in our case, new and existing reservoirs and their management rules, and irrigation developments) reach the best achievable balance between performance objectives across the WEF sectors and the environment (SI sections S3 and S4). The optimization is an automated process whereby a computer initially randomly combines the different development combinations and their management options and refines them through an iterative search process (Maier et al., 2014, 2019; Nicklow et al., 2010; Reed et al., 2013). The decisions considered by the search include the activation of irrigation schemes with differing seasonal patterns and magnitudes of water demand, activation of new reservoirs, and release rule parameters of new and existing dams. The search is directed by quantified measures referred to as "performance metrics"; that is, the search will identify those combinations of development interventions which are most efficient. Efficiency is defined in the sense of economic Pareto-optimality; that is, it finds those combinations of options which cannot be further improved upon except by sacrificing performance in one or more other metrics. We employ the Epsilon-Dominance Non-dominated Sorted Genetic Algorithm II (Kollat & Reed, 2006; Tang et al., 2006) linked to the water impact model via a wrapper code (please see SI section S3.2 for more details).

3.2. Performance Indicators

The use of appropriate performance measures to evaluate river basin developments aims to ensure assessment results are relevant to stakeholders and decision makers. Performance objectives were identified through literature review and stakeholder consultation. Literature consisted of Rufiji river basin reports (WREM International Inc., 2015) and earlier modeling studies (Kashaigili et al., 2005, 2006; Lankford, 2004; Lankford et al., 2007), environmental flow assessments, and more general literature on the basin (e.g., Duvail et al., 2014). Multiple stakeholder consultations involved people identified through previous exercises plus extensive local consultation and comprised government staff (primarily in the Rufiji Basin Water Board and the Ministry of Water), hydrological and environmental researchers from universities, and several locally active NGOs working on sustainability and development issues. Consultations took the form of small interactive workshops (8 to 20 participants) held in March 2017, March and November 2018, and July 2019, complemented by informal discussions with many individuals (from the

Table 2
Development Scenarios Considered in This Study

Development scenario	Decisions made	Rationale
1) Current	No new development, optimized (best achievable) management rules of current assets	Manage what you have.
2) Current + JNHP	Same as 1 but includes JNHP	Best accommodation of the new dam.
3) Synergistic	Optimized combinations of planned irrigation and dam options and their management rules	Synergistic constellations of energy, irrigation, and environmental interventions.
4) Full	Full development of all planned irrigation and dam options with optimized management rules	An attempt at economic development "at all cost."

organizations listed above) between January 2016 and July 2019. This produced a long list of initial indicators that was narrowed down to nine (Table 1) which were defined by the stakeholders through consensus during the November 2018 workshop with consideration of their usefulness (particularly their representation of key features across the WEFE sectors in the basin) and data availability (see section 4 for details).

Informant interviews were conducted during March 2019 to ground the trade-off results in a national and regional political decision-making context. The respondents were purposively sampled from governmental and nongovernmental institutions knowledgeable and/or involved in processes of agricultural expansion and land use change in the Kilombero subcatchment and more widely in the Rufiji river basin (more details in SI section S5). This follows the "issue-based approach" of political economy analysis as per Booth et al. (2016), which aims to identify systemic factors, political uncertainties in processes, and actors' decision logics and power play. Insights from the interviews were used to design the scenarios of irrigation expansion and to interpret and discuss the results in relation to understanding of drivers and policy and management responses (section 3.3).

3.3. River Basin Development Scenarios

This paper argues that WEFE nexus system development assessments need to be able to consider different extents of river basin development; optimizing only a single framing of basin development is inappropriately restrictive. We introduce "development scenarios" as a way to accommodate different views on a WEFE system's development. The development scenarios considered in our case study were informed by published government plans and workshop discussions about different trajectories of basin development, such as where irrigation expansion may occur and what interventions are likely to be bundled together (Table 2). For example, now that the JNHP is going ahead, it is generally viewed as less likely that other run-of-river hydropower plants will be built; this is considered in one of our development scenarios. For each development scenario, we optimize reservoir operating rules of (existing and proposed) dams so that the development scenarios can be compared on a like for like basis, assuming coordinated management of upstream and downstream assets. While the scenarios assess "best case" of coordination of infrastructure, this is not guaranteed given the basin is managed by several authorities.

The first two development scenarios consider the "Current" river basin and the addition of only the JNHP. A third "Synergistic" scenario optimizes a combination portfolio of irrigation expansion, whereby only those options are implemented that contribute to the Pareto-optimal solution. The fourth "Full" development scenario assumes the full development of all planned infrastructure expansion. The possibility of reducing the storage size of the JNHP and its impact on performance is considered under the Synergistic and Full development scenarios.

As a further refinement of the Synergistic scenario, we consider a future where irrigation development not only consists of expansion but also addresses the inefficiency of scheme operations and the impact of autonomous and largely unregulated smallholder irrigation that often surrounds them. We assume that with better management and stronger enforced regulations, local nonbeneficial irrigation consumption (evaporative conveyance losses, weed transpiration, and evaporation) and nonrecoverable return flows can be reduced and irrigation return flows can be preserved and become available for downstream use, as represented by the IRFR increasing from 35% to 55% for both existing and new schemes.

4. Data and Implementation

Irrigation water demand, including return flows, at demand node locations is provided by the hydrological model. Actual realized water withdrawal is calculated by the water resources system management model based on availability of surface water. Total irrigation water demand for the present (baseline) is simulated at 2.2 BCM, and this increases to 8.7 BCM with planned irrigation expansion to 400,000 ha, with return flows to the river of 1.7 BCM. These figures are in line with estimates provided in WREM International Inc. (2015). This results in a potential net increase in demand of ~5 BCM for irrigation, set against a mean annual discharge for the Rufiji of just over 30 BCM (Siderius et al., 2018). Current irrigation in the basin is based on MIRCA2000, a global data set of cropping patterns of 26 major crop types for the year 2000 (Portmann et al., 2010), with cropped areas updated to capture major recent changes in land use (between 2000 and 2008–2010) using Tanzanian government statistics (Ministry of Agriculture of the United Republic of Tanzania, 2017). For 2035, the National Irrigation Commission under the framing of the National Irrigation Masterplan proposes an increase in irrigation from 111,000 ha of irrigation in 2010 to 400,000 ha in the basin (WREM International Inc., 2015). About a third of this expansion is explicitly defined in the model as four large planned irrigation schemes: 23,000 ha of sugarcane in the Kilombero subcatchment (associated with the ILLOVO plantation), 18,000 ha earmarked for expansion in USAID feasibility studies (CDM Smith, 2016), 6,260 ha of rice in the Usangu subcatchment, and about 69,000 ha downstream of the JNHP. The other two thirds of planned expansion consists mostly of small- and medium-sized schemes and is spatially allocated using the following rules: (1) no expansion in game reserves or national parks; (2) prioritizing SAGCOT districts; and (3) prioritizing cells with existing irrigated area and then cells with existing agriculture (assuming these to be most suitable due to existing infrastructure) and restricting total cropped area to 90% of cell area. In the Rufiji river basin, there are three major irrigated crops simulated: rice, maize, and sugarcane. Other crops, like tomatoes and onions, were clustered under a fourth "other" category. A distinction between dry and wet season specific irrigation expansion was made (with rice as the wet season crop and dry season expansion targeted as other crops). A multiobjective optimization search is conducted for each of the development scenarios simulating the system on a monthly time step using 30 years of historical flow data. Details and information sources of hydropower dams, run-of-river plant characteristics, and wetlands included in the water resources simulation model are provided in SI section S2; Table S3 lists the hydropower dam characteristics, Table S4 the run-of-river plant characteristics, and Table S5 the characteristics and how the wetland systems in the basin are simulated.

While subject to rapid development, the Rufiji river basin is very sparsely monitored relative to its size and importance. and therefore, we stress that the modeling results are illustrative and numerical values should be taken as such.

5. Results

In this section, we present the different efficient (Pareto-optimal) designs under each development scenario. The results show the different sets of efficient trade-offs between hydropower, irrigation performance, and environmental benefits and reveal how benefits depend on the size and location of new dams and on the timing and magnitude of reservoir releases. Figure 4 shows the different levels of benefits achievable under the different development scenarios. Each point in the scatter plots of panels (a) and (b) and each line in panel (c) parallel axis represents a constellation of existing and proposed infrastructure developments and their management rules. For any achievable mix of preferences or priorities between the benefits (the metrics optimized in the search), the plots show the best achievable performance.

Panel (a) shows potential to improve irrigation water supply while increasing the irrigated area (e.g., design labeled "a" and "n"). Implementing all potential irrigation sites (shown with "m" in panels (a) and (c)) deteriorates irrigation water supply leading to deficits. Panel (b) shows how a small sacrifice in energy generation leads to large improvements in the environmental metric (e.g., by selecting "h" or "j" instead of "d" or "f"). Panel (c), a parallel axis plot, shows the performance of selected designs, designated with letters in panels (a) and (b) (the ones that maximize at least one of the performance objectives). In all panels, arrows indicate preferred direction of performance. In panel (c), performance improves from the bottom to the top of

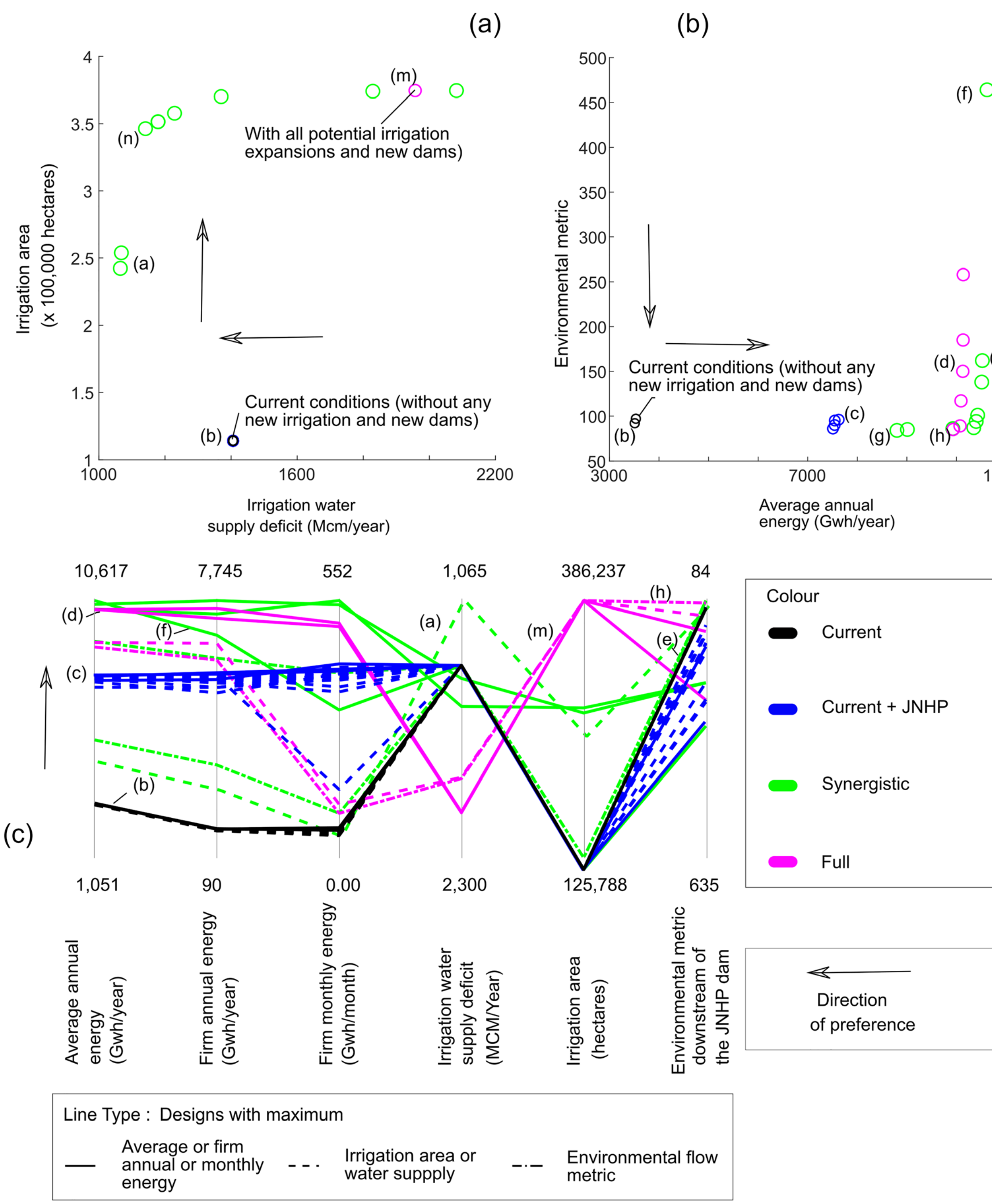

Figure 4. Trade-offs in performance implied by best performing designs under the four development scenarios. Each circle (in panels (a) and (b)) and solid line (in panel (c)) represents the best performance obtained by an approximately Pareto-optimal combination of developments. Performance improves in the direction of the arrow in each panel.

each axis such that an unachievable "perfect" design would be a straight line across the top. Solid, dashed, and dash-and-dot lines show designs with the best performance in energy, irrigation, and environmental metrics, respectively, for each development scenario.

Figure 4a shows the trade-off between irrigation area and irrigation water supply deficit. Improvement in irrigation water supply (lower deficits) can be achieved with further dams although supply reliability degrades with the last 50,000 ha of irrigation expansion. This occurs because upstream abstractions reduce water availability and because some of the irrigable area is upstream of the dams and cannot be impacted by them. Figure 4b shows the possibility of reducing environmental impacts by maintaining the natural

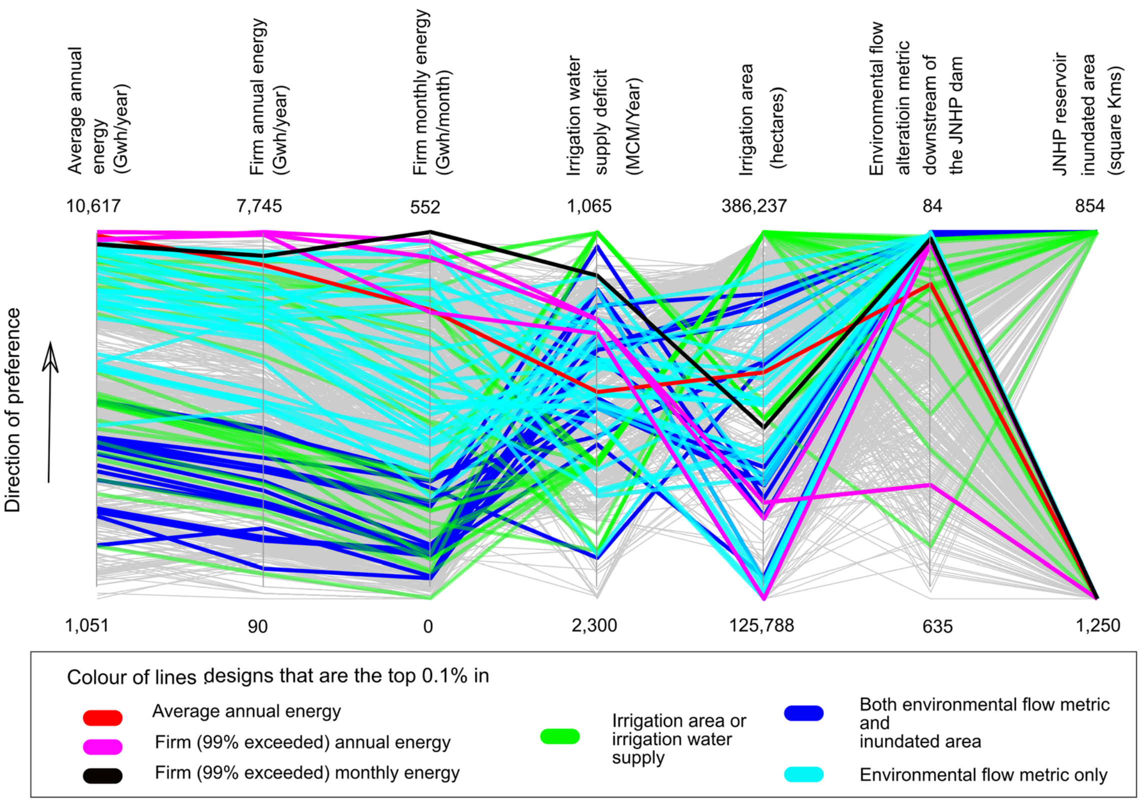

Figure 5. Multiobjective optimization with seven WEFE performance indicators. Each solid line represents the best performance obtained by an approximately Pareto-optimal combination of interventions in the Synergistic development scenario. Red, magenta, green, and blue lines show designs with the highest performance (top 1% of full sample) across six performance metrics (Table 1). Performance improves from the bottom to the top of each axis (i.e., an unachievable "perfect" design would be a straight line across the top of all the axes). The minimum performance values shown for each axis (at the bottom of the axes) indicate the threshold value after which any further increase in that performance leads to a reduction in at least one other performance objective.

hydrologic variability with relatively small sacrifices in energy generation (e.g., moving from point "d" to "h"). Comparing efficient designs under the Synergistic and Full (green and magenta) development scenarios shows the ability to maintain the natural flow regime is not significantly affected by upstream development. As demonstrated by the variable environmental performance under similar infrastructure (e.g., blue and magenta lines in Figure 4c), the ability to maintain the natural flow regime is controlled by reservoir operating policies. Note that the reduction in energy production imposed by full development is higher than the energy sacrifice needed to reduce environmental impacts (e.g., compare performance between designs "h," "j," and "d" in panel (b)).

Figure 4c shows the performance of selected designs (those designated by letters in panels (a) and (b)) for multiple metrics. The values at the top of the six parallel axes represent the highest achievable performance if that particular objective were to be prioritized. The lines between the axes represent efficient (Pareto-optimal) designs; they are the development bundles achieving all feasible combinations of human preferences between the six objectives in the plot. Lines that cross between two adjacent axes signal a trade-off between those measures; the steeper the angle, the stronger the trade-off between the two performance indicators. The performance difference between the Current, Current + JNHP, and Synergistic development scenarios shows significant potential for irrigation and energy expansion. Comparing scores of designs "b," "c," and "d" on the leftmost axis shows that the JNHP, which is under construction, is the highest contributor to the overall hydropower potential of the Rufiji river basin. In Synergistic, the number and type of development options are allowed to vary along with the reservoir operating rules. In Current and Current + JNHP, irrigation areas are fixed. Optimized mixes of the development options achieve higher performance in energy and irrigation metrics than where all options are implemented in the Full development scenario (e.g., compare "d" with "f" and "a" with "m" in Figure 4c).

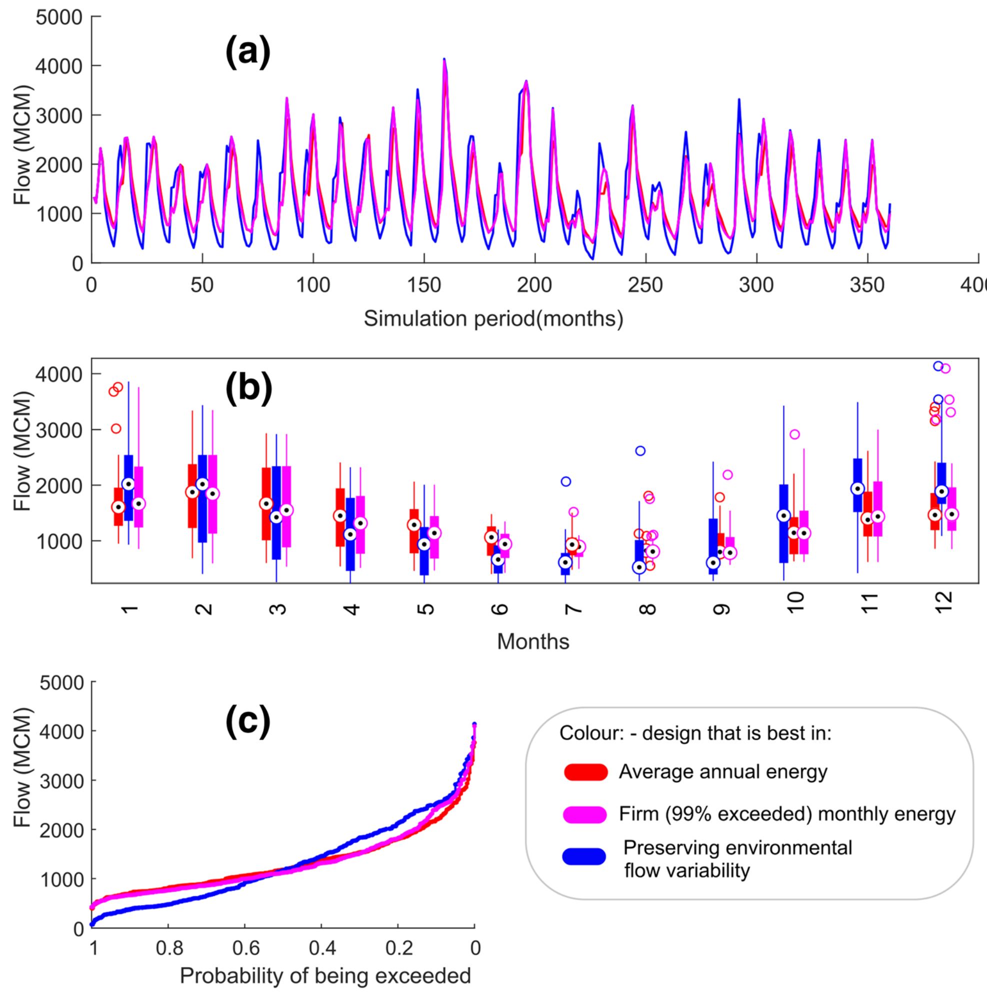

Figure 6. Simulated monthly releases from the JNHP dam under different release policies from the Synergistic development scenario. (a) Time series, (b) the monthly distribution flows, and (c) their cumulative distribution functions.

Figure 5 shows performance relationships with the full set of Pareto-optimal designs (not just those with letters in Figures 4a and 4b) for the Synergistic scenario only. Results show development potential in energy of 10.6 TWh/year on average of which 7.7 TWh/year is firm annual energy (that can be exceeded 99% of the time). Designs that prioritize one of the energy performance objectives (red, magenta, and black lines in Figure 5) impose low environmental performance. However, designs which achieve the highest environmental performance objective (cyan lines in Figure 5) can achieve as much as 99% of the average annual energy potential of the basin, but their firm annual and firm monthly energy performance will be lower. It is not possible to reliably meet irrigation demand if all the irrigation options are developed; increase in irrigated area results in higher irrigation deficits.

Figure 6 shows what the environmental flow alteration metric downstream of JNHP represents. The plot shows various views of the distribution of flows under flow regimes optimized for preserving flow variability (blue) or to optimize for firm monthly (magenta) or average annual (red) energy production. The ideal environmental flows in blue preserve flow variability, an important factor in maintaining ecological river health.

The extent of the JNHP impact on the former Selous National Park is controversial (IUCN, 2019; The Citizen, 2019). Figure 7 shows the effects of optimizing the storage size of the JNHP to reduce its storage size and hence the inundated area in the National Park.

Figures 7a and 7b show the relationship of the environmental flow metric and inundation area with other performance objectives (assuming the lower return flow). The firm monthly and firm annual energy

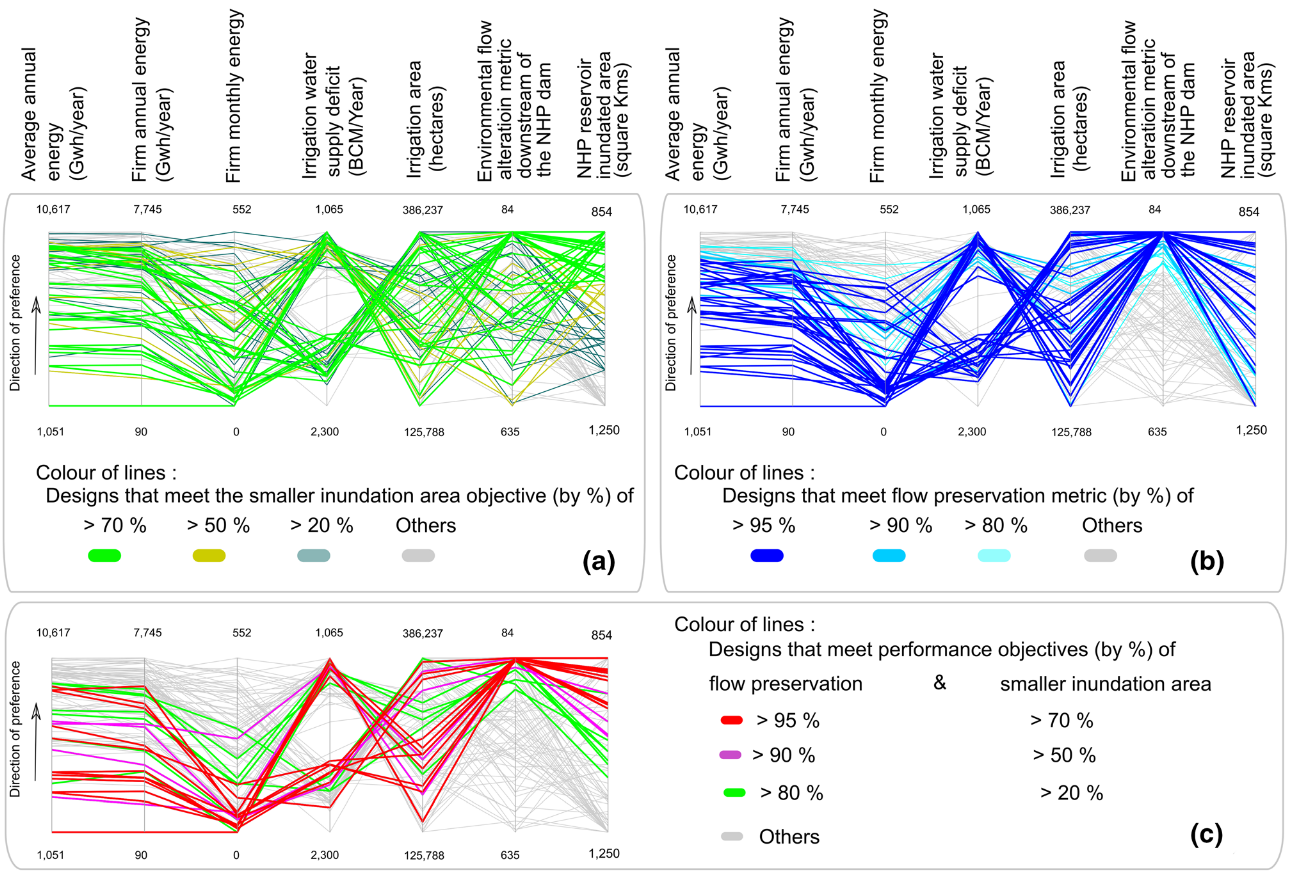

Figure 7. Performance trade-offs for optimized Synergistic designs considering variable JNHP storage size and designs that meet various levels of environmental performance objectives (i.e., maintaining natural flow variability downstream of the JNHP and minimizing the surface area inundated by the new reservoir). Line colors in panels (a) and (b) show performance of designs when one environmental performance objective is considered at a time. Panel (c) shows performance of designs that simultaneously do well on both environmental metrics but lead to poor firm monthly energy production. Vertical axes are the same for all panels.

performance is impacted more than the average annual energy for a unit change of the two environmental metrics. Some 90% of the average annual energy generation potential of the Rufiji can be achieved while keeping the potential envionmental flow metric within the best 10% (the highest energy score of the cyan lines in panel (b)). The rate of decrease in the average annual energy for a unit decrease in inundated area is low. However, the reduction in the firm (99% exceeded) annual energy and firm monthly energy could be much higher (compare the highest score of colored lines in panel (b) in the first three parallel axes).

Reducing the storage size of the JNHP dam would help reduce the environmental impact on the National Park by diminishing the inundated area. For example, reducing the reservoir's inundation area by 30% results in a reduction of 8%, 9%, and 23% in average annual, firm annual, and firm monthly energy generation capacities, respectively. Maintaining the natural flow variability (restrict environmental flow metric to the top 10%) requires a reduction of 11%, 16%, and 29% in the average annual, firm annual, and firm monthly energy generation capacities, respectively. Applying the above requirements together would impose a reduction of 16% in the average annual and firm annual and a 73% reduction in firm monthly energy generation capacities. Designs represented with red, magenta, and green colors in Figure 7c achieve higher percentage of the potential average annual energy compared to the firm monthly energy. This shows that the environmental performance objectives of reducing the reservoir inundated area and maintaining the natural flow variability have a more significant trade-off with firm annual and firm monthly energy than with average energy generation.

Figure 8 shows the impact of improving the IRFR compared to the impact of implementing optimized system designs in the Synergistic development scenario. Trade-offs between the three energy indicators and

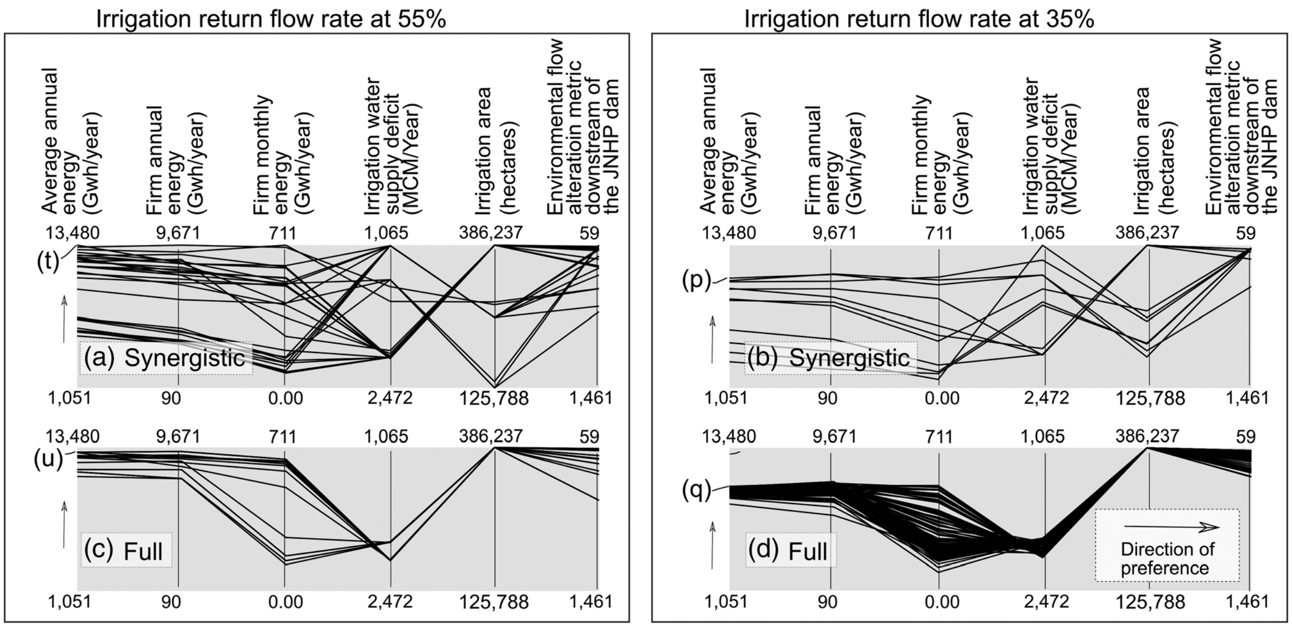

Figure 8. Multidimensional performance under different development scenarios (a–d). Performance improves from the bottom to the top of each axis (i.e., an unachievable "perfect" design would be a straight line across the top of all the axes). The relative improvement in energy generation if the irrigation return flow rate were to be increased (shown by lines "t" and "p" compared to lines "u" and "q" respectively) would be higher than the increase from optimizing new developments (difference between "t" and "u" or "p" and "q" lines).

irrigation expansion are much reduced due to the increased availability of return flows if upstream irrigation is better managed. Figure 8 also shows that the gains, for example, in energy production, are larger from better managing irrigation (maintaining high return flows) than from optimizing the number and location of irrigation schemes.

6. Discussion

Interventions to achieve development in WEFE nexus systems often have multidimensional impacts and cross-sectoral interdependencies that can be analyzed by tracking multiple performance measures simultaneously and their trade-offs. In this paper, we have demonstrated a rigorous way to assess and reconcile (compare consistently) differing extents of river basin development by comparing their optimized trade-offs, that is, seeing what are the best-case trade-offs between WEFE sectors achievable for each extent of river basin development, as characterized by four different development scenarios. River basin managers are seeking best possible outcomes, but there can be no single optimized level of development in a river basin, as each individual or organization will have their own vision on what this is. Therefore, the WEFE nexus design approach used here accommodates different extents of development scenarios and summarizes visually for each one how river basin benefits can be distributed between sectors and regions (upstream-downstream).

6.1. Implications of Intervening in the Rufiji River Basin

An application to Tanzania's Rufiji river basin showed large potential for irrigation and energy expansion before water resource limitations impose trade-offs between the two sectors under the climate conditions of the past 30 years. The addition of the JNHP (blue line in Figure 4c) contributes a major part of the energy potential, particularly the firm monthly energy, because the large storage makes water available for hydropower production. Although optimized designs that maximize one of the three energy performance objectives (shown with red, magenta, and black lines in Figure 6) generally result in low environmental performance, some designs with high energy performance also do well for environmental flows (e.g., "d" and "h" in Figure 4) but with small decreases in energy potential. Results showed the ability to maintain natural hydrologic regime of flow variability with relatively small sacrifices in energy generation (Figure 4b).

Unregulated irrigation expansion will constrain additional energy generation from the basin by up to 2 TWh/year (Figure 8). With rapid change underway in large parts of the basin, irrigation governance is challenging (Mwamakamba et al., 2017). However, we show that if local nonbeneficial irrigation water consumption and nonrecoverable return flows are reduced through better management and stronger enforced regulations, the impact of upstream development on downstream energy production and environmental conditions can be strongly minimized. These gains are larger in the Synergetic development scenario—the optimized mix of possible development options—than in a "develop-full" scenario.

Reservoir operating policies that minimize changes to the natural variability of flows (i.e., improve the environmental flow metric downstream of the JNHP dam) or a reduction in the JNHP storage size to avoid inundating large areas of the Nyerere National Park have a greater impact on the achievable firm annual and firm monthly energy generation performance than on the average annual generation performance (Figure 7). Results (Figure 7c) show energy generation from a smaller reservoir would be less reliable (in firm annual and firm monthly energy metrics), especially if maintaining the environmental flow regime is also a priority. If the JNHP reservoir is to be built and high reliability of energy generation is important, a larger reservoir is preferred.

6.2. Management and Policy Considerations

We recognize that there are assumptions and values incorporated within any trade-off analysis and that such exercises sit within a wider political process involving to varying degrees many actors, perceptions, and differing social values and preferences (BBC, 2018; Hoag & Öhman, 2008; WWF, 2018). Achieving consensus can be challenging, even with political will and concerted effort; the approach presented here can make a valuable contribution to such a process. The suggested approach helps stakeholders use the simulation-optimization process to iteratively learn about the system, refine their optimized metrics, and deliberate optimized "best-achievable" trade-offs in order to arrive at a negotiated acceptable mix of development options and their benefits which are then presented to decision-makers.

The water resource management modeling system makes assumptions about the nature and effectiveness of management practices. Past events have highlighted issues with coordination of dam releases contributing to reduced electricity generation (Yawson et al., 2003) and weak coordination between sectors (Pardoe et al., 2018). Other factors, experienced more widely in sub-Saharan Africa related to underinvestment, governance, and weak implementation (Conway et al., 2017; Escribano et al., 2010), also apply in the Rufiji basin.

Political will, manifested through budget allocation, to address the problems highlighted above and deliver effective and equitable policies, will be critical to the viability of proposed developments. On a positive note, a recent alignment between conservation of upstream ecosystems via water conservation for downstream energy generation has emerged. Reportedly, a high-level dialog started in April 2019 at the Vice President's Office initiative between the ministries of Energy, Natural Resources and Tourism, Agriculture, and Water to discuss the issue and propose a solution (informant interviews, 2019). This, coupled with increased productivity of land as promoted by the SAGCOT initiative via improved irrigation schemes and better input use, could be an avenue for greater water conservation for downstream energy generation.

6.3. Technical Considerations

Detailed information on irrigation extent and water use is sparse throughout the basin, with estimates on present and potential areas of irrigated land varying between reports (Yang & Wi, 2018), and so our estimates of water use and the effects of improving irrigation management should be taken as illustrative. Irrigation expansion in many parts of sub-Saharan Africa has been far slower than planned (Mwamakamba et al., 2017), and plans for formal irrigation expansion in the Rufiji river basin are currently below official targets. At the same time, informal agricultural expansion, both irrigated and nonirrigated, has progressed rapidly (Godoy et al., 2012; Harrison et al., 2017). The water resource system model is conditioned on historical data from the Rufiji Basin Water Management plan (WREM International Inc., 2015). Given the challenges of coordinated multipurpose water infrastructure management in practice, our estimates of energy production should also be considered as estimates of best achievable performance.

We have considered seven performance metrics identified through background research and stakeholder consultations; this is relatively low for a complex basin such as the Rufiji but sufficient to capture first-order interdependencies across the WEFE sectors and their environmental linkages. Nevertheless, the number and formulation of performance metrics have an important bearing on the results and their interpretation. For example, the environmental flow indicator is quite simple (see SI section S6) and only represents one site (the flow regime immediately downstream of the planned JNHP, Figure 1) while there are many important other ecosystem services and possibly useful indicators throughout the basin. With the JNHP, the upstream impact might seem relatively small; however, the activity triggered by the construction (e.g., road access) might intensify poaching and ecosystem degradation in a larger area (UNESCO, 2014). Further research could help assess whether the pattern of biennial flooding of the downstream delta, important for maintaining deltaic lakes, wildlife, fisheries, and downstream flood recession agriculture (Duvail et al., 2014), could also be maintained.

Our optimization includes irrigation options as on or off but does not optimize their size. Future studies could consider scaled expansion of individual irrigation options. Allowance could also be made for a more detailed representation of the wetlands and considering future climate change impacts on river flows. This study focuses on trade-offs implied by conditions known today. This particular study does not seek to optimize robustly, that is, over multiple plausible futures, nor does it try to schedule interventions in time or consider the time value of money (discounting). The explicit consideration of multiple sources of uncertainty in the optimization (e.g., Hurford, Harou, et al., 2020; Huskova et al., 2016) and timing of investments (e.g., Erfani et al., 2018; Geressu & Harou, 2019), although compatible with the methods used here, is left to future Rufiji studies.

Portraying relationships between two performance metrics at a time may aid comprehension (e.g., Figure 4), but informed decision making across multiple sectors requires simultaneous consideration using visualizations like the parallel plots (Figures 5, 7, and 8). In actual decision situations, the parallel axis plots (Inselberg, 2009) are best used interactively with stakeholders so that they can rearrange the position of the axes (as crossed lines between adjacent axes indicate trade-offs) and filter out axes values that are deemed unacceptable (Kasprzyk et al., 2013; Kollat & Reed, 2007).

7. Conclusions

WEFE nexus systems are complex to manage and plan because of interdependencies between sectors, regions, and interventions over space and time. We have described an approach to reconcile, that is, to compare consistently, different extents of river basin development. We use a multiobjective optimization process that identifies mixes of proposed hydropower dams and irrigation sites that achieve various efficient balances of performance objectives under different visions of basin development that we organized into development scenarios. Our results highlight important basin-scale interdependencies, where performance indicators are impacted at downstream dams due to upstream cumulative effects of unregulated irrigation expansion and inefficient management, something that may remain difficult to regulate in the future.

Four river basin development scenarios, ranging from the current system to full development, have been considered. Overall, the Rufiji river basin has the capacity to support a range of development plans. Results show that average annual energy generation from the Rufiji under synergistic and full development scenarios will be impacted more by low irrigation return rates than by sacrifices needed for environmental (ecosystem well-being) purposes (i.e., maintaining flows close to the natural hydrologic regime). As the decision to build the JNHP dam has been made, we focused our analysis on how it could be impacted by upstream development and the presence and operation of other proposed dams by 2030. Maintaining current levels of nonrecoverable return flows has substantial (up to 11%) negative impact on hydropower potential. In all three future development scenarios, optimized release rules for the JNHP reveal the potential to closely replicate the natural variability of the river flow and hence substantially reduce the negative impact of the reservoirs. While trade-offs with average annual energy production are minimal, this does have a considerable impact on firm annual and monthly energy performance metrics.

The value of such a multicriteria WEFE trade-off assessment is high for quantifying and visualizing the multisector effects of decisions and comparing alternative options and their consequences considering a range benefits. However, model-based decision support should be seen as part of a wider process of decision making—our results are illustrative (due to assumptions in the modeling and data availability)—for actual decisions, and such an approach would, among other things, need to be set within a wider and deeper consultation process to make it more inclusive, to consider the merits of the number and derivation of performance metrics used, and to explore the effects of differing levels of management and coordination across sectors and the upstream-downstream parts of the basin. The optimized development scenarios are able to achieve balanced outcomes across performance metrics, but this is contingent on coordination between sectors and between upstream-downstream infrastructures. Our results highlight the scale of performance reduction at downstream investments (mostly hydropower production at downstream dams) that a failure to check upstream expansion would mean and the level of irrigation expansion that can be achieved while maintaining acceptable performance at downstream investments.

Data Availability Statement

Data that support our analysis are described in detail in the hydrological modeling paper by Siderius et al. (2018). The crop-hydrological model is open source (can be downloaded from www.pik-potsdam.de), as is the water resources model (Matrosov et al., 2011). Primary hydrological data are available at the Rufiji Basin Water Board Office in Iringa, Tanzania.

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