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Assessing sustainable development pathways for water, food, and energy security in a transboundary river basin

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A B S T R A C T

Worldwide hundreds of millions of people suffer from water, food and energy insecurity in transboundary river basins, such as the Zambezi River Basin. The interconnected nature of nexus is often not recognized in investment planning and many regional policymakers lack adequate tools to tackle it. Future growing demands and climate change add an additional challenge. In this study, we combine policy relevant co-developed stakeholder scenarios and integrated nexus modeling tools to identify key solutions to achieve sustainable development in the Zambezi. Results show that siloed development without coordination achieves the least economic and social benefits in the long term. Prioritizing economic benefits by maximizing the use of available natural resources results in the expansion of irrigated areas by more than a million hectares and increase in hydropower production by 22,000 GWh/year in the coming decades, bringing significant economic benefits, up to $12.7 billion per year, but causes local water scarcity and negative impacts on the environment. Combining environmental protection policies with sustainable investments of $7.2 billion per year (e.g. groundwater pumping and wastewater treatment and reuse, irrigation efficiency improvements, and farmer support aimed to improve food security and productivity) results in significantly higher social benefits with economic benefits that still reach $11.7 billion per year.

1. Introduction

The growing demand for energy, food and water have exerted significant pressures on natural resources during the last decades, sometimes compromising the functioning of ecosystems and the vital services they provide (Jägermeyr et al., 2017; Pastor et al., 2019; Veldkamp et al., 2017). Population growth and increasing standards of living amplifies the challenge to meet these demands sustainability (Bauer et al., 2016; Greve et al., 2018; O'Neill et al., 2017; Popp et al., 2016; Riahi et al., 2016). Climate change could further exacerbate this challenge, by affecting water availability and quality, increasing the occurrence and severity of extreme events,

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and reducing crop yields, among many other impacts (Elliott et al., 2014; Mosley, 2015; Prudhomme et al., 2014; Schewe et al., 2014a; Whitehead et al., 2009). As such, regional policymakers need to adapt current management practices and investments to secure a reliable future supply of sustainable energy, food and water. However, adaptation options are often constrained by competing objectives and uncertainty related to future socioeconomic and climatic changes, and at the same time involve multiple stakeholders with different priorities. Therefore, an appropriate choice of options should be informed using an integrated nexus framework which combines qualitative methods and quantitative tools. In recent years, the scientific community has embraced the concept of nexus to specifically recognize the energy, food and water sectors as interconnected and interdependent, encouraging the shift from a sectoral focus on production maximization to improving cross-sector efficiencies (Hoff, 2011; Kahil et al., 2019; Wada et al., 2019). The value of the nexus approach increases in transboundary and developing river basins such as the Zambezi River Basin (hereafter referred to as the Zambezi), where major sectoral investment plans are considered and impacts may spread from one country to another.

As one of the largest river basins in Africa, the Zambezi basin has significant water, land, and other natural resources and covers an area of 1.4 million km^2 spanning over eight countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe) (Fig. 1). The basin is home to more than 40 million people, where livelihoods in the region are tied to agricultural development and are characterized by high levels of poverty and food insecurity (Phiri et al., 2017). The population of the basin is estimated to reach almost 80 million by 2050 and the GDP to grow by about 5% per year (Dellink et al., 2017; Fricko et al., 2017; KC

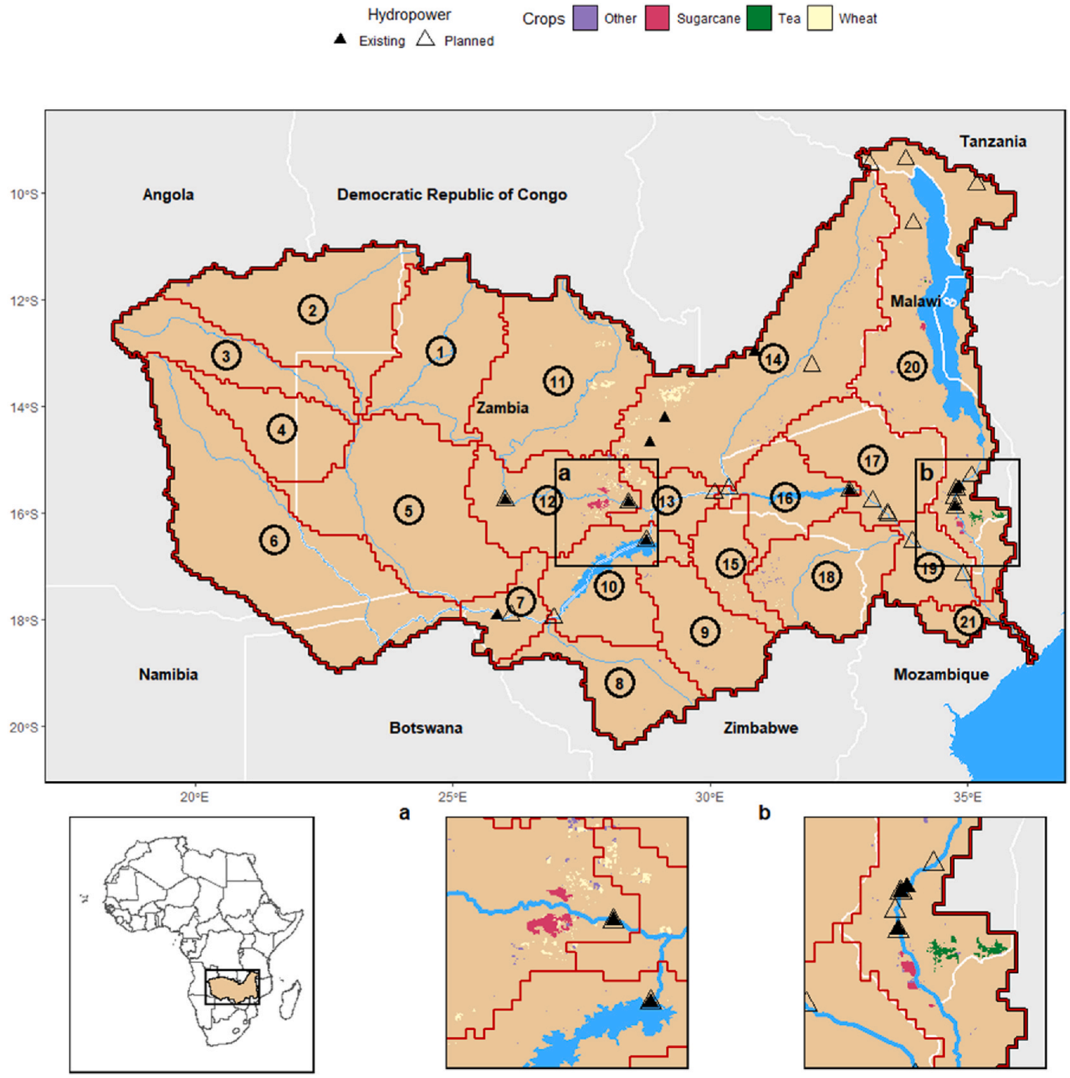

Fig. 1. Installed and planned hydropower and main irrigated crops around the year 2010 within the Zambezi River basin (large map): Numbers indicate the 21 subbasins distinguished in the modelling framework (SI Section 3.2, Fig. S6, and Table S2). Basin and subbasin borders are rasterized using a 5 arcmin resolution for modeling purposes. Insets show irrigated cropland areas and hydropower facilities in two selected subbasins where hydropower and irrigated areas are in close proximity: (a) Upper Kafue wetlands and (b) Shire River. Source: Authors' own elaboration of data sources.

and Lutz, 2017) (SI Table S8 and S9).

Owing to the abundance of water resources, investing in hydropower and irrigation has long been considered as the means for realizing the economic potential of water resources in the Zambezi (World Bank Group, 2010a,b,c). Moreover, significant investments in water, sanitation, and hygiene (WASH) infrastructure in the region are required to improve the poor WASH services and keep up with the region's growing population. With successful investments the region could achieve many of the United Nations' Sustainable Development Goals (SDGs) related to poverty alleviation, improved health, food and energy securities, and economic prosperity.

Hydropower generation is one of the major economic activities in the Zambezi, with an installed capacity of about 5000 MW supplying electricity to riparian countries and neighboring countries through the Southern African Power Pool. Future hydropower expansion plans in the Zambezi, as seen in Fig. 1, include more than 11,000 MW of new large-scale hydropower projects (Cervigni et al., 2015; Mulligan et al., 2020; Spalding-Fecher et al., 2016; World Bank Group, 2010a,b,c, hydropower facilities described in SI Section 4.6, SI Table S11 and S12, SI Fig. S19). Currently, about 183,000 ha of cropland area in the Zambezi is irrigated, representing only 5% of the region's irrigation potential (Frenken, 2005). Various irrigation projects under development could bring an additional 336,000 ha over the coming years, while more optimistic, ambitious irrigation plans estimate that an additional 1.2 million ha could be brought into production (World Bank Group, 2010a,b,c).

These major investment plans have been developed independently and without conducting an integrated assessment of the potential negative trade-offs that could emerge among these competing sectors at the water-energy-land nexus (Spalding-Fecher et al., 2016). Examples of such nexus trade-offs include impacts of upstream irrigation water withdrawals on hydropower generation downstream and impacts of decisions to release reservoir water for use by agriculture or store it for future electricity generation. Moreover, these investments do not consider or have a limited view of the impacts of future socioeconomic and climatic changes, implications for downstream countries and sectors, stakeholders' preferences, and the need to fulfill environmental commitments such as minimum environmental flow requirements and climate change mitigation.

Despite the significant contribution of previous studies focused on future sectoral investments in the region (such as those from Payet-Burin et al. (2019), Spalding-Fecher et al. (2016), Tilmant et al. (2012) and World Bank Group, 2010a,b,c), most did not subject their assessments to the impact of long-term climatic trends combined with socioeconomic development which significantly impacts the regional supply and competing demand for water, energy, and food. These studies relied heavily on exogenous future trends and presented little to no linkage between the basin and the larger Southern Africa region and global market context which impacts the profitability for energy and agricultural products (See SI Section 3).

In this study, we explore the water, energy and land nexus interactions using an integrated nexus modeling framework (INMF). The INMF incorporates local data, solution focused co-designed scenarios, and state-of-the-art hydrological, hydro-economic, crop growth, water quality, and economic land use models. We apply the INMF to the Zambezi to evaluate three future basin scenarios that combine various policies and investments under future climate and socioeconomic changes and examine the impacts on the basin over a wide set of nexus indicators in order to understand the sectoral trade-offs within the water-energy-land nexus and management options that make achieving the basin's development goals possible.

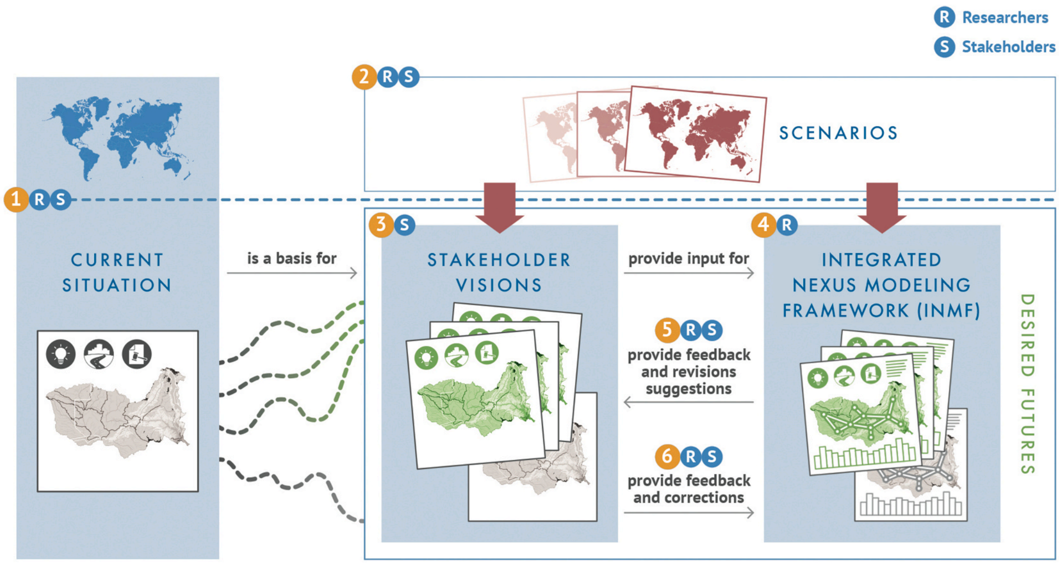

Fig. 2. Summary of the process describing the participatory approach to the development of the basin scenarios Note: R: Researchers; S: Stakeholders. Source: Authors' own elaboration reproduced from the ISWEL Project Progress report (Willaarts et al., 2018); Graphic design: Bartosz Naprawa.

2. Methods

To address the nexus challenges of the Zambezi, we combine a participatory approach to co-develop with stakeholders a set of future pathway scenarios with quantitative integrative modeling of the scenarios and nexus solutions. This study makes use of multiple visions of future pathways and a wide range of nexus management solutions (e.g., adoption of efficient irrigation systems, use of groundwater and non-conventional water sources, optimal allocation of water resources, and food trade) to achieve multiple development goals. Our stakeholder approach (2.1) was carried out and the INMF (2.2) developed through the Integrated Solutions for Water, Energy and Land (ISWEL) project with the support of the Zambezi Watercourse Commission (ZAMCOM).

2.1. Stakeholder engagement and participatory approaches to explore the nexus

The stakeholder scenario development process is based on a participatory multi-scale design aimed to produce policy relevant results (Karner et al., 2019; Kok and van Delden, 2009; Palazzo et al., 2017) which is further elaborated in Wada et al. (2019) and in the ISWEL Project Progress Reports (Willaarts et al., 2017, 2018). Drivers influencing potential development pathways in the Zambezi occur at different scales, from local to global, and are differentiated by the so-called “sphere of uncertainty” and “sphere of influence” (van Notten, 2006). In order to act as a bridge between science and policy, our approach considers the measures and policies, so-called decision units (Zurek and Henrichs, 2007), to which basin stakeholders (Zurek and Henrichs, 2007) have the ability to agree and to adopt (sphere of influence), as well as important global developments and potential external shocks and uncertainties which belong to the stakeholder decision context. Local planning processes need to adapt to uncertainties to achieve the desired water, energy and land development goals in the medium to long term.

The objectives of stakeholder engagement, summarized in Fig. 2, were to identify country and basin development priorities and the main nexus challenges based on stakeholder preferences and views that could be represented within the modeling framework and to co-develop alternative basin visions and sustainability pathways.

We facilitated two participatory consultations with regional stakeholders and researchers and a number of bilateral meetings from 2017 to 2020. From the first consultations, we synthesized the development priorities and nexus challenges facing the basin (step 1 in Fig. 2), while in parallel, adapting different, future global development scenarios to provide external challenges for the stakeholders to consider (step 2 in Fig. 2). Using this challenge context, we co-developed future pathways and visions for the basin focusing on water, energy, land, and overall development goals for 2050 (step 3 in Fig. 2). The nexus challenges of the basin at present and the visions were quantified using the INMF (step 4 in Fig. 2) and presented to various stakeholder groups to get feedback and refine the framework and scenarios (step 5 and step 6 in Fig. 2).(See SI Section 1)

2.2. Integrated nexus modeling framework

To assess the tradeoffs within the water-energy-land nexus and potential management solutions we developed the INMF that links, in a consistent way, well-established hydrological, hydro-economic, economic land use, crop process and water quality models,

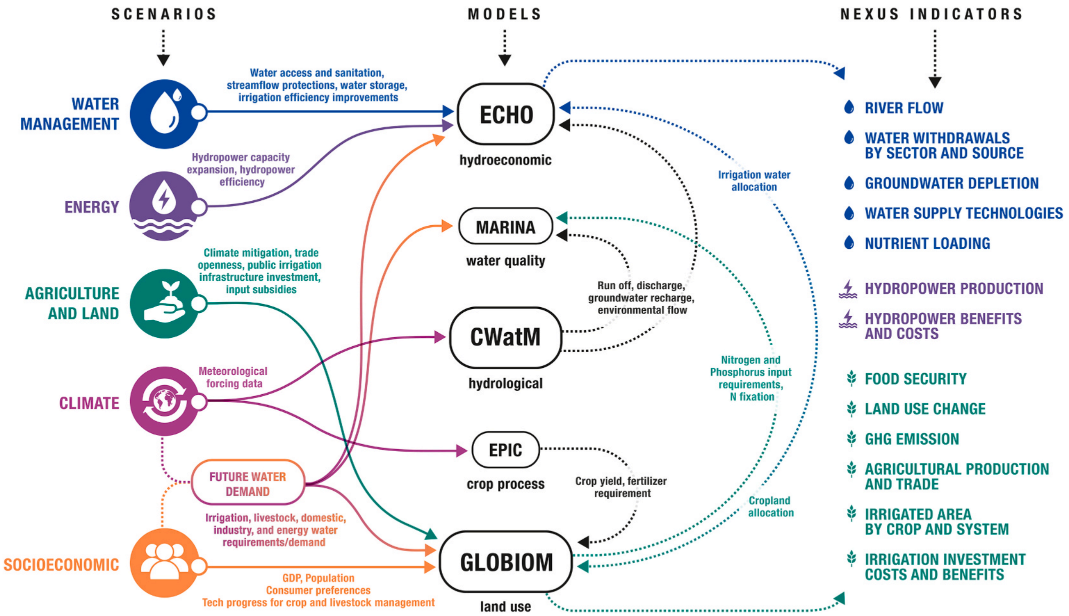

Fig. 3. Schematic overview of the integrated nexus modelling framework (INMF) for the Zambezi River Basin. Source: Authors’ own elaboration; Graphic Design: Adam Islaam

represented schematically in Fig. 3. Our modular framework allows for the detailed representation of single systems, with the consistent linkage among these systems, facilitating a more effective integrated optimization of nexus management solutions. The modeling framework uses 21 distinct and linked subbasins within a hydrological network to model the water dynamics for different water sources and demand sectors across the network of eight riparian countries (SI Section 3.2 provides detail on the subbasin delination). The representation of global trade and socioeconomic development, market feedbacks in the framework allows the impacts of the basin-level analysis to be globally consistent (Palazzo et al., 2017).

The INMF can assess basin-level development plans or policies for managing water, energy and agriculture. The modular and scalable approach allows the detailed representation of each sector with input data or quantitative modeling results to be upscaled from households and land units to sub basins. Although the INMF is used to assess nexus trade-offs at a basin level, the basin can also be analyzed across a network of eight countries. The INMF evaluates impacts of *investments* in water access and sanitation, hydropower expansion, irrigation development, *policies* for climate mitigation and streamflow protections, and *regional trends* in socioeconomic development and climate change.

The integrated nexus modeling framework (INMF) links process-based hydrological (CWatM (Burek et al., 2020)) and crop modeling (EPIC (Balkovič et al., 2013; Williams and Singh, 1995)), water quality (MARINA (Strokal et al., 2016; Wang et al., 2019, 2020)) and economic optimization models of land use (GLOBIOM (Havlík et al., 2011; Pastor et al., 2019)) and water use (ECHO (Kahil et al., 2018)).

The Community Water Model CWATM is a fully open-source, large-scale integrated hydrological and channel model which calculates water availability (surface and groundwater) and environmental flow requirements, as well as the socio-economic water demands and impacts from water infrastructures such as reservoirs, groundwater pumping, and irrigation (Burek et al., 2020). CWatM provides indicators at the sub-basin level basin of run-off, discharge, groundwater recharge, and environmental flow requirements.

ECHO is a bottom-up linear optimization model of the water system that includes an economic objective function and represents the most relevant biophysical and technological constraints (Kahil et al., 2018). ECHO provides indicators at the sub-basin level of water use and withdrawals from hydropower, agriculture, municipal and industrial uses, water supply technologies, and water supply costs and benefits.

The Global Biosphere Management Model (GLOBIOM) is a global partial equilibrium model that is used to model the supply and demand of agricultural products at a high spatial resolution in an integrated approach that considers the impacts of global change (socioeconomic and climatic) on food, feed, and fiber markets (Havlík et al., 2011; IBF-IIASA, 2023). GLOBIOM provides indicators of regional crop and livestock production and demand, international trade, land use change and emissions, food security, irrigated area by crop and system, water demands for irrigation, and irrigation investment costs and benefits.

EPIC (Balkovič et al., 2013; Williams and Singh, 1995) is a globally gridded crop growth model that uses pixel-level biophysical conditions to simulate crop yields, nutrient and water requirements for crop products at a high spatial resolution. The model is used to simulate biophysical processes of agricultural ecosystems and used to estimate spatially explicit crop productivity potentials and input requirements to reach those potentials (nitrogen, phosphorous and water) for 17 crops (Balkovič et al., 2013).

The Model to Assess River Inputs of Nutrients to seAs (MARINA) (Strokal et al., 2016) is a nutrient model that quantifies river export of different nutrient forms (dissolved organic and inorganic nitrogen and phosphorus) to the river mouth by source at the sub-basin scale on an annual basis. It quantifies dissolved nutrient export by rivers as a function of human activities on land and nutrient retention in rivers, lakes and reservoirs.

The three primary models (CWatM, ECHO and GLOBIOM) included in the INMF use the same harmonized input data (subbasin map and network and scenario assumptions), and they are soft-linked: relevant output of one model is used as input into the other model. The exchange of information between models ensures that nexus challenges, trade-offs and synergies are modelled in an integrated way. As an example of this integrated linkage, CWatM provides projections of water availability including runoff, groundwater recharge, environmental flow requirements, and municipal, and industrial water demands to ECHO. GLOBIOM projects and passes on the water demand for irrigation and the relative profitability of irrigated crop production when water is considered unlimited (i.e. unconstrained irrigation water availability) to ECHO. ECHO can then determine the optimal allocation of water to the different sectors (irrigation, hydropower, households and industries) based on each sector's profitability and taking into account various technical and environmental constraints. ECHO considers the river routing and takes into account how water is retained, used, or transferred to downstream users across the basin. The optimized water allocation and change in water price for irrigation is used as an input into GLOBIOM to run for the final time. The different water demand projections from GLOBIOM provide different insights: the "unconstrained run" provides an upper bound of irrigation potential if water scarcity is not considered and irrigation takes into account only the relative profitability of the crops grown under irrigation systems and the run with full "CWatM-ECHO-GLOBIOM" chain takes into account the water balances and relative profitability of each water demanding sector and considers the benefits from infrastructure investment in different sectors.

The supporting models (EPIC and MARINA) provide input data or assess the impacts of the main model outputs: crop yield and input requirements for different management systems are simulated by the gridded crop model EPIC and nutrient loading is assessed by the MARINA model. EPIC provides GLOBIOM information on the change in crop yield due to changing climatic conditions and input requirements under different management systems (Leclère et al., 2014). Changes in cropland area, crop production and fertilizer application are passed from GLOBIOM at the subbasin level along with runoff and discharge from CWatM to MARINA which quantifies the nutrient loading from agricultural production and domestic wastewater. The individual model components of the INMF and Zambezi basin data sources used by the modeling framework are further described in the SI Section 4: Detailed model descriptions.

The INMF assesses the impacts of climate change on precipitation and irrigation water demand using projections from global circulation models (GCMs) based on the IPCC emission scenarios (IPCC AR5). The calibrated Zambezi basin outputs produced by

CWatM were compared with the hydrological model ensemble (Schewe et al., 2014b) from the inter-sectoral impact model inter-comparison project (ISI-MIP) fast track data (Warszawski et al., 2014) under the RCP 6.0 scenario (See SI Section 4.6: Data sources).

3. Results

3.1. Nexus scenarios for development

The three co-developed pathway scenarios of our study are centered around stakeholder identified challenges and visions for the future of water, energy, and land in the basin. The future visions consider the prioritization of different possible development plans and environmental goals at local and basin scales.

The scenarios, as summarized by Box 1 below and described qualitatively in SI Section 2, provide context for various assumptions on policies for water management, agriculture and land, and energy and climate, which were then included in the INMF and quantified to the year 2050. In the "Business-as-usual" **BAU** scenario each sector considers surface water as the main source for water supply with little coordination across sectors and basins and with no investment in alternative water sources. In the "Economy First" **ECN** scenario, achieving economic development in the basin, by maximizing hydropower production and expanding irrigation, is prioritized over protecting the environment. In the "Environment First" **ENV** scenario, the Zambezi aims to achieve development goals both for the environment and for society.

A detailed description of the scenario narratives and an extended overview of the modeling assumptions used for each scenario based on the stakeholder consultations, basin development plans, plausible socioeconomic and climate regional trends can be found in SI Section 2 and SI Section 4.6.1 and Table S1. Per capita income growth trends based on the "Middle of the Road" Shared Socio-economic Pathway (SSP2) assumptions project an annual increase of about 3.1% over the period and the climate trends are based on RCP 4.5 which projects an increase of 2° warming by 2050.

The INMF relies on a detailed representation of different biophysical processes and impacts and considers the economic feasibility of the different development scenarios. We then use the framework to examine economic, social and environmental impacts of future scenario pathways and compare the impacts across scenarios to identify potential trade-offs and solutions at the water-energy-land nexus. In Fig. 4 we visually represent these tradeoffs by comparing the value of eight indicators in the year 2010 (in red) with their values across the scenarios in the year 2050. For ease in comparing across the economic, social, and environmental benefits, the numbered indicators have been rescaled with the scale of the axis noted next to the unit of measurement. In the following sections, we examine the economic benefits and sectors contributing to the nexus trade-offs revealed by the scenarios.

3.2. Economic feasibility of development and nexus solutions along the pathways

Results show that the future developments in the Zambezi are expected to substantially increase food and energy production and related benefits (e.g., food security, trade surplus, financial gains) over the coming years (Fig. 4: indicators 1, 4, 7, 8 and Fig. 5) starting in 2020 onward in the time period (Fig. S21). The projected increase in the region's population coupled with a growing per capita income (on average of 3% per year) drives the increase the region's demand for food across all scenarios. The increase in calorie availability due to the rising incomes reduces the share of the population at risk of hunger across all scenarios from 45% to only about 12% of the population by 2050 (Table S16).

Box 1
Brief scenario narrative assumptions. Source: Author's own elaboration based on stakeholder workshop discussions

Business-As-Usual	Economy First	Environment First
• Energy: Hydropower capacity expansion fully developed • Agri./Land: Moderate investments in irrigation and crop input subsidies, no carbon tax • Water: Maximize surface water use, low level of water, sanitation, and hygiene investment (WASH), no env. flow constraints • Trade: Limited openness of agricultural trade	• Energy: Hydropower capacity expansion fully developed • Agri./Land: High investments in irrigation and expanded crop input subsidies, no carbon tax • Water: Optimize all water sources, allow inter-basin transfers and new storage, promote efficiency, medium level of WASH, no env. flow constraints • Trade: Increasing openness of agricultural trade	• Energy: Hydropower capacity expansion fully developed • Agri./Land: Moderate investments in irrigation and crop subsidies for climate smart (CSA) practices (e.g., crop diversification), carbon tax on emissions from LUC • Water: Maximize use of groundwater, high level of WASH, env. flow prioritized • Trade: Limited openness of agricultural trade

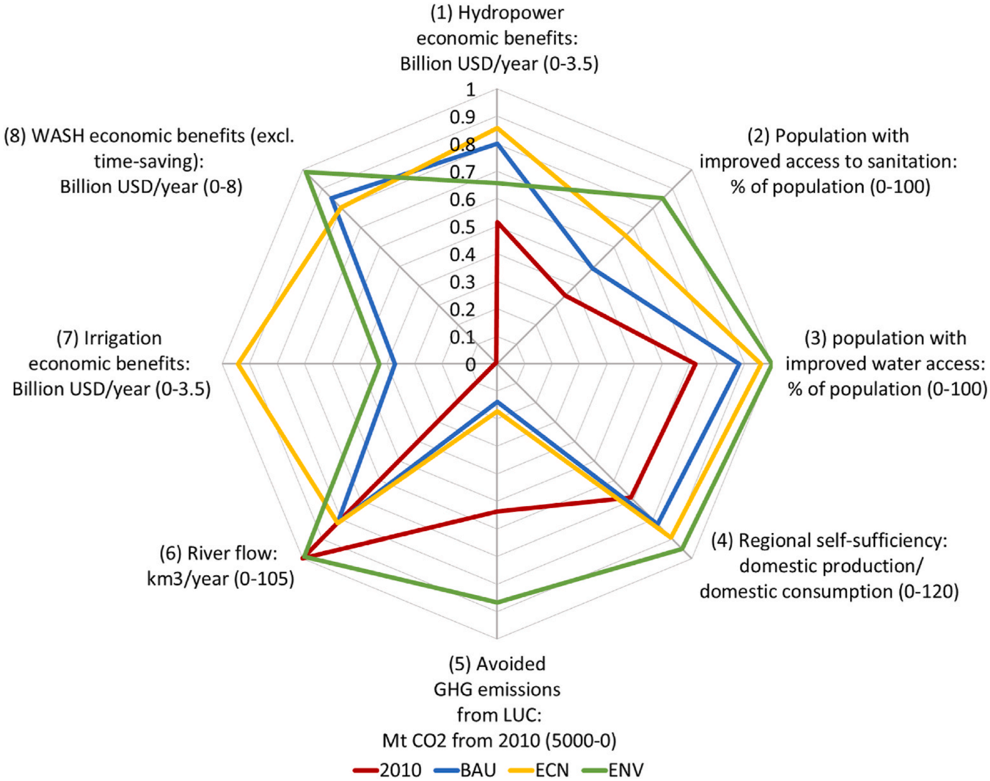

Fig. 4. Economic, social, and environmental benefits in 2010 and 2050 across Zambezi scenarios. The indicators (numbered 1–8) have been rescaled according to the dimension indicated next to the unit of measurement. The more outward indicator appears from the origin of the figure the greater the benefits. Source: INMF Modeling Results.

The economic benefits of hydropower production will increase from 1.8 billion USD/year in 2010 to 2.3–3 billion USD/year in 2050, which will quickly cover the cumulative capital costs to expand capacity in existing facilities and construction costs for new downstream projects which have been estimated at 12.5 billion USD (World Bank Group, 2010a,b,c) (Fig. 4: indicator 1 and Fig. 5, Figs. S31 and S32). At present, the annual water sector costs are estimated at 1 billion USD per year representing roughly 3% of the basin's current GDP. Ambitious irrigation expansion plans, which would add an additional 1M ha in the ECN scenario, can only be achieved when large scale infrastructure costs that enable irrigation expansion (e.g., water delivery from water source to field and capital replacement costs for equipment) are considered public goods and covered by public funds. The private net revenues from irrigation for farmers will increase about 10% per year over the time period in the BAU and ENV scenarios, and about 12% per year under the ECN scenario reaching about 3.3 billion USD per year in net revenues, coming from expansion in higher yielding irrigated crops such as sugarcane, oilseeds, rice and wheat production (Fig. 4: indicator 7, Fig. 5). Results indicate also that subsidies to reduce farmer production costs (e.g., fertilizer and improved seeds) enable the region to transform from a net importer of crop products in 2010 to a net exporter of crop products by 2050 in ECN and ENV (both in terms of traded volumes and in embedded calories of the trade volumes), with the greatest share of calorie exports occurring in ENV scenario (primarily with countries in Eastern Africa and the Congo Basin), owing to the expansion of subsidies for farm production costs for cereals but expanded to include legumes, roots, and tubers (Fig. 4: indicator 4). Zambezi consumers also respond to the lower prices, resulting from the investments to reduce producer costs, by consuming the most (in calories per capita and in calories domestically produced) in the ENV scenario (SI Section 4.3.3 GLOBIOM Demand and Trade and Table S16).

Presently, only about half of the population in the countries of the Zambezi have basic access to drinking water, a third have access to piped drinking water, and only a third have access to sanitation (WHO/UNICEF Joint Monitoring Programme, 2019) (SI Table S15). Investments in water infrastructure of up to 7.5 billion USD per year are needed to realize the significant economic and social benefits that come from improving water access and sanitation and expanding irrigated area (Fig. 4: indicator 2, 3, and 8 and Fig. 5). The economic benefits for human health and productivity for population with improved access to clean water and sanitation are estimated to more than double the investment costs (Hutton, 2012, 2015), with about half the economic benefits (between $6.1 billion in ECN and $7.5 in ENV) coming from reduced morality, increased productivity and reduced healthcare costs (Fig. 4: indicator 8, Fig. 5). WASH economic benefits would be significantly higher if accounted for additional benefits, such as time-saving which could double the current WASH benefits (Fig. S32)) The sustainable development of the Zambezi (ENV scenario), which prioritizes not only environmental protection but increased water access and sanitation and sustainable agricultural development and hydropower expansion, would not result in a dramatic reduction of private benefits, it could rather increase social benefits (Figs. 4 and 5).

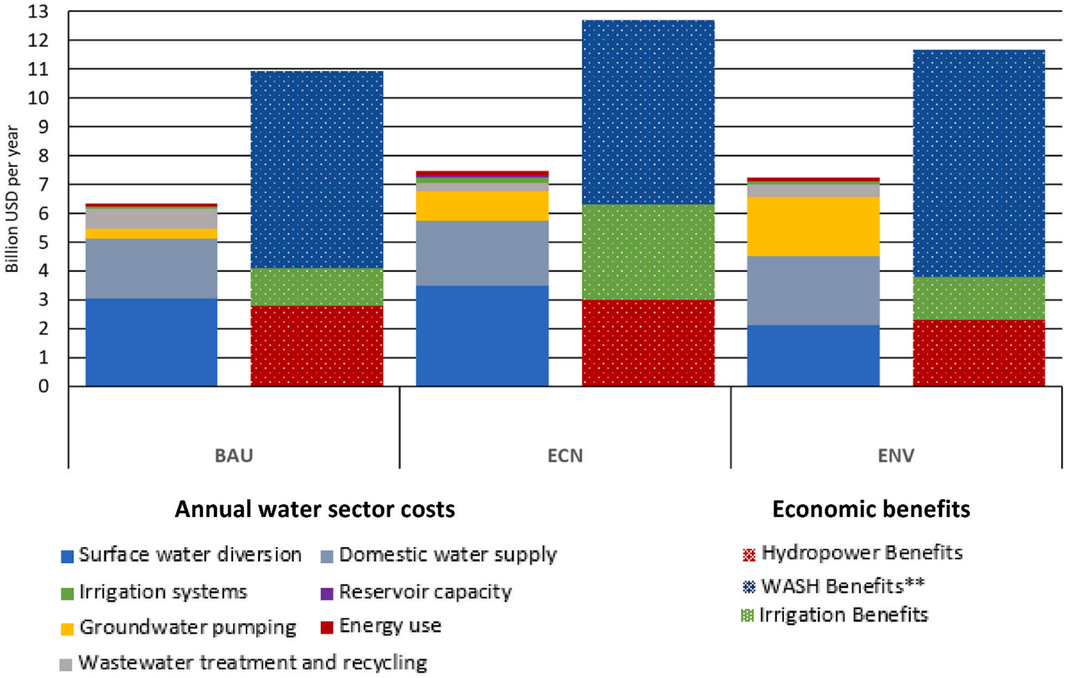

Fig. 5. Economic costs and benefits of the scenarios in billion USD per year. Note that the annual water sector costs include (investment and operation costs of raw water pumping, irrigation systems, reservoir capacity, and water access and sanitation) and WASH benefits only include those attributed to reduced mortality, increased productivity, and reduced health care costs. Source: INMF Modeling Results.

3.3. Trade-offs in the water, energy, and land nexus

3.3.1. Environmental protections on streamflows and land-based mitigation policies (water-land-energy)

Future joint developments of hydropower and irrigation could create negative impacts on river flow, water quality and forests, especially in mid and downstream sub-basins, in the absence of environmental protection policies (Fig. 4: indicator 5 and 6). Without enforced environmental flow protections, the withdrawals for irrigation, domestic use, and water storage for hydropower reduce the river flow to the sea by 18% in 2050 compared to 2010 levels.

The water scarcity index (WSI) of the basin as a whole, calculated using the average monthly water use divided by the average monthly surface water available, increases from a low level of water scarcity of around 20% in 2010 to 34–56% in 2050 in the scenarios (medium water scarcity for ENV, high water scarcity for BAU and ECN) (SI Section 5.3 Water scarcity across the basin). The levels are adapted from Alcamo et al. (2007), values less than 20% are considered low water scarce, values between 20% and 40% are medium water scarce, values between 40 and 70% are considered highly water scarce, and values from 70% to 100% are considered extremely water scarce. Future increases in domestic water demand, expansion of irrigated areas and hydropower developments raise the level of water scarcity to extreme levels in eight of the most populated subbasins under the BAU and seven subbasins in the ECN scenario as shown in Fig. 6 (SISection 5.3 Water scarcity across the basin, Table S18). At a subbasin level, without environmental streamflow protections the future co-development of irrigation and hydropower will lead to extreme water scarcity in the Kafue (12) and further exacerbate the existing extreme water scarcity in the Shire River (20) (Fig. 6, SI: 5.3 Water scarcity across the basin and SI 5.5 Subbasin Analysis, and Table S18).

More than 21 million ha of forest area (about 10% of the forest area) could be deforested for use as cropland and grassland if policies to limit biodiversity loss and AFOLU greenhouse gas emissions are not adopted and enforced (SI Section 5.4, SI Table S16, and SI Figs. S24 and S25). At the subbasin and local level, the expansion of cropland and grassland areas may have significant impacts if it occurs at the expense of locally important forested areas or natural lands. Land-based mitigation policies, such as carbon taxes on emission from land use change, do not significantly limit agricultural development opportunities, as productive cropland area expands by converting grassland/pastureland and other natural lands which have a lower carbon content, sparing forests from land use change and reducing GHG emissions from land use change (from about 150 Mt CO_2 eq/year to less than 2.5 Mt CO_2 eq/year) (Fig. 4: indicator 5).

3.3.2. Impact of hydropower on water and land (energy-water and energy-land)

Utilization of water for hydropower production is generally considered temporary water storage, as the water will eventually be released downstream, however, reservoirs and dams, including those built for hydropower generation, increase the surface area of streams and lead to more evaporation than would take place naturally (Kohli and Frenken, 2015). The largest increase in surface water utilization is expected to take place in locations where planned hydropower facilities will come online in 2030 (Fig. 1; SI Tables S11,

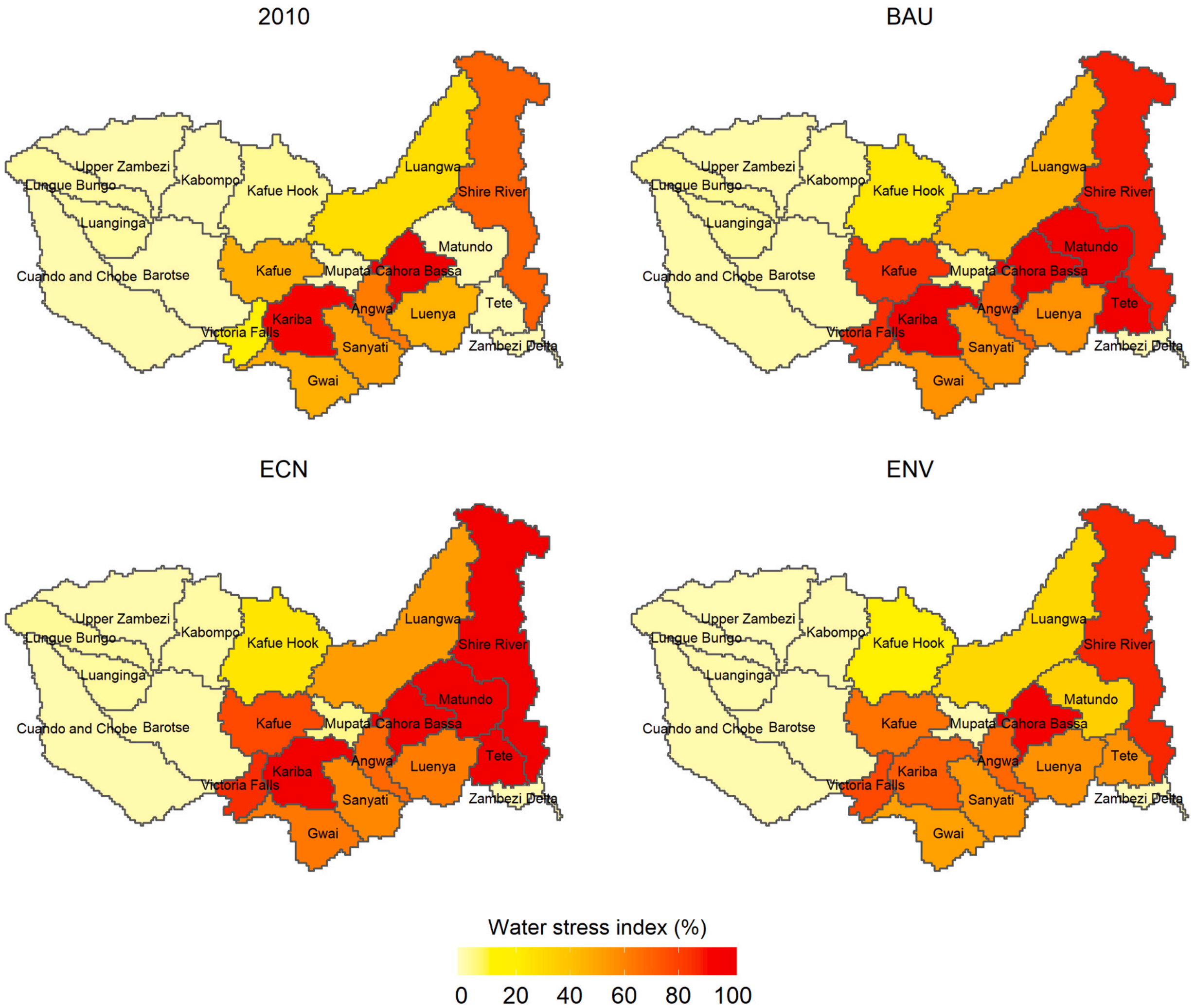

Fig. 6. Water stress index (average monthly surface water utilization as a share of the average monthly available surface water) in the 21 subbasins in 2010 and 2050 across Zambezi scenarios. Source: INMF Modeling Results.

S12, and S19). Evaporation from reservoirs and dams of the Zambezi are responsible for substantive losses, about 12 km^3 per year, primarily from the Kariba (10) and Cahora Bassa (16) dams. Our modeling results are consistent with other studies showing that evaporative losses will stay relatively the same in the future (Kling et al., 2014). Subbasins with currently operating hydropower facilities are considered extremely water scarce, and that scarcity will continue to worsen in the future due to increased water storage for hydropower production (Fig. 4: Kariba (10) and Cahora Bassa (16), Table S18). While subbasins with planned facilities will see a shift from low water scarcity at present to extreme water scarcity by 2050 in BAU and ECN, this scarcity is mitigated to some extent with environmental flow protections (ENV) (Table S18).

The temporary water storage of dams and reservoirs may limit irrigation development if water diversion is restricted during critical growing periods in order to maintain adequate water levels for hydropower production (Hoekstra, 2003; Spalding-Fecher et al., 2016). Under BAU, when hydropower production is prioritized over irrigation development and surface water remains the only source of water for irrigation, 381,000 ha of irrigated area can be added to the basin (SI Table S16), however with conjunctive use of surface water and groundwater (ECN scenario, SI Figures S22 and S23) more than 1 million ha of irrigated area can be added, making it one of the major solutions for shared water resources for the Zambezi.

3.3.3. Increased demand for alternative water sources for irrigation and domestic water use (water-land)

Each subbasin's overall increase in water withdrawals comes from further utilization of surface water, however, in Kafue (12) and Shire River (20) groundwater use is projected to significantly increase by 2050 in the ECN and ENV scenarios (see SI Figures S22, S23, and S30 Table S17 Section 5.5 Subbasin Analysis). Wastewater recycling capacity is also projected to expand in several subbasins including Shire River (20), Gwai (8) and Angwa (15) (SI Figs. S23 and S27). The significant increase in the conjunctive use of water resources (from surface water, groundwater, and recycled wastewater) in the future demonstrate that the growing demand from multiple sectors cannot be met by increasing surface water withdrawals alone. Furthermore, we find that conjunctive use is only partially driven from upstream basins' surface water withdrawals affecting downstream users. Increasing future climate variability, as well as the Zambezi River's natural intra-annual and inter-annual variability, and prioritization of surface water for hydropower may lead subbasins to expand groundwater withdrawals and wastewater recycling.

4. Discussion

4.1. Economic benefits and investments

Sustainable environmental and economic benefits from hydropower and irrigation development will require large, coordinated investments (SI Section 5.6 Water supply costs and benefits). National governments and international financial institutions would be the most likely investors for irrigation developments and domestic water access and sanitation, while hydropower investments would come from private companies already operating in the basin. Coordination and cooperation are critically important between sector stakeholders and among the national actors in the basin, on which our study and the World Bank Group (2010a) study agree. However, the World Bank study found that investments to achieve ambitious irrigation plans had a negative economic impact on hydropower expansion plans, though their assessment did not consider the conjunctive use of surface water and groundwater, which we have found to be a solution to achieve multiple development goals.

Ancillary benefits from hydropower production, agricultural development, improved access to clean water and sanitation and avoided deforestation that are not centered in our study such as ecosystem services, job creation and rural economic development may be significant. The ecosystem service benefits from avoided deforestation due to the policies in the ENV scenario (Fig. S24) could be as high as 3.6 billion USD per year (145 billion USD over the period) when using the value of ecosystem services for tropical forests from Costanza et al. (2014) and Rosegrant et al. (2023). The Programme for Infrastructure Development in Africa (PIDA) estimates the job creation of the Batoka Gorge hydropower project could be around 27,000 jobs over the life cycle of the project with 88% considered as secondary jobs created due to the economic impact of the project due to increased energy and transport (AUDA-NEPAD, 2019). In our study, the Batoka Gorge hydropower project is projected to account for about 20% of the new hydropower capacity in the basin which means that the remaining new basin hydropower capacity could create about 108,000 jobs over the lifetime of the projects. The working age population employed the agrifood system in the different Zambezi countries may be highly variable and rapidly changing (e.g., rising in urban areas, dominated by young workers from ages 18–34, declining in the share of the total population engaged in farming) (Jayne and Yeboah, 2016). The increase in crop productivity for farmers and increasing share of exports for rainfed (e.g., corn and sorghum) and irrigated (e.g. sugarcane) crops will provide transformative change in farmer livelihoods that are necessary to adequately scale up the opportunities for economic growth and jobs in the off-farm agri-food sector (e.g., marketing and transport, food manufacturing, food preparation) (Tschirley et al., 2015).

4.2. Solutions to the water-energy-land-nexus

For the Zambezi to achieve its economic development and environmental goals, the region should consider supporting actions and investments that provide solutions across the water, energy, and land nexus. In the following sections we discuss several solutions for the basin.

4.2.1. Continued regional cooperation and integration

Inter-governmental organizations like ZAMCOM, which provide a cooperative network for water managers, are essential institutions (Sadoff and Grey, 2005). Among river basins that span across multiple international boundaries, ZAMCOM has been successful in ensuring that its member countries have trust, joint-ownership of infrastructure and respect the shared-use principles. Since ZAMCOM was officially established in 2014, its activities have included collecting and sharing real-time streamflow data with water managers and organizing an annual stakeholder meeting to share insights and concerns. The technical unit of ZAMCOM discusses and engages with policy makers to provide evidence-based support and assessments of strategic planning for water resources within the basin. The future scenarios of this study were developed with ZAMCOM partners and assumed that integrated, basin-wide strategic planning continues.

4.2.2. Investments to increase crop yields and transform smallholder agriculture

Farming in Southern Africa is primarily smallholder, low input cultivation, with relatively low agricultural productivity. Increasing the productivity of crops in the Zambezi basin, and in sub-Saharan Africa generally, should be a priority for investment. Rising per capita income tends to result in increased agricultural productivity (Evenson, 2001). In the region, it is expected that crop yields will increase by 40% by 2030 and double by 2050 due to the rising economic growth and investment in agricultural research and development, extension services. Subsidizing farm inputs, such as fertilizer and improved seeds, improving access to local and international markets, and prioritizing and expanding extension services to support the adoption of climate smart agricultural (CSA) practices can help transform smallholder, subsistence farming by improving the productivity and profitability (Hanbal et al., 2021). The design of these programs, farm input subsidy programs in particular, should be routinely evaluated to assess their effectiveness in increasing agricultural productivity and to limit the unintended economic and environmental effects (Hanbal et al., 2021). Crop diversification, which plays a role for agricultural development in this study's ENV scenario, is among the CSA practices that shown to increase land productivity, and improve farmer livelihoods and rural development (World Bank Group, 2019). Historically, developed countries have also used public water infrastructure investments to spur agricultural development, among other goals (Toan, 2016; Van Koppen et al., 2005; Wichelns, 2010). These types of investments may significantly improve the reliability of water available for irrigation to increase crop yields while also reducing the capital investment costs for irrigation infrastructure for farmers (Palazzo et al., 2019).

4.2.3. Improved irrigation efficiency

Irrigated areas shift toward more efficient systems when the expansion of agricultural land is limited, and water constraints are binding (SI Section 5.4.1 and SI Figure S26). However, the difference in areas under efficient irrigation by scenario suggests that strong land and water policies may incentivize the conversion of flood systems to highly efficient irrigation systems or conversion of rainfed areas to highly efficient irrigated areas while policies and investments that make water available to farmers or further reduce the water supply costs may not. Policies and investments aimed to improve the irrigation and water use efficiency for farmers could target investments such as land levelling to improve flood/gravity irrigation systems, extension outreach to improve irrigation scheduling, or improved and timely water distribution (Miao et al., 2018). Crops like sugarcane require monthly irrigation and are often irrigated by efficient sprinkler systems. However, even these irrigation systems could benefit from investments which increase the water application efficiency.

4.2.4. Food trade

Investments to develop irrigation in the basin make progress on meeting the growing demands for food and feed, especially for rice and wheat, and the region achieves net self-sufficiency for some crops, however, the region will still need to import some products from outside the region to meet the growing demand (Fig. 4 indicator 4, SI Section 5.8 and SI Figure S33 and S34). Improving rainfed crop yields (especially for maize) is essential as the region is heavily dependent on maize. Support for producers, including farmer extension services and input subsidies to facilitate the adoption of CSA practices will be key to maintaining shifting the region into a trade balance for some of the crops (e.g. maize and legumes). Most studies of irrigation development for the region do not usually consider irrigation of roots, tubers, and legumes since these crops are typically not irrigated, however, field studies have found that cassava and chickpeas may respond well to irrigation (Odubanjo et al., 2011; Singh et al., 2016). Allowing for non-traditionally irrigated crops to shift into irrigation production depending on their profitability, we found that by 2050 irrigated production contributes significantly to meeting food demand for rice, wheat, sugarcane, soybean, chickpeas, potatoes, and cassava. Irrigation of non-traditionally irrigated crops could be a solution to improve food regional self-sufficiency (chickpea, cassava) but further field testing in the basin is necessary.

4.2.5. Conjunctive use of surface water and groundwater and water storage

For many Zambezi subbasins, low surface water flows for several months of the year are a natural part of the hydro-climate system. Conjunctive and sustainable use of groundwater for irrigation may be a major solution for the Zambezi and certain sub-basins in particular, not only when surface water withdrawals are limited by environmental flow requirements, but also as a way to allow hydropower to take priority of surface water (SI Tables 17 and 18, SI Figs. S22, S23, S28 and S29). Investments in expanding reservoir capacity for use other than hydropower may also provide a solution to low surface water flow conditions during dry months (SI Section 5.7: Reservoir Capacity and SI Table S19). The domestic sector benefits the most from an expansion in water storage for most of the subbasins (Kafue Hook, Gwai, Angwa, and Sanyati) with an expansion for Luenya and Luangwa in which irrigation also benefits. However, a more detailed assessment of the sustainability of such investments in storage and groundwater pumping needed to minimize the negative environmental impacts.

4.3. Water-energy-land nexus in the SDG context

The SDGs are transversal; individual goals depend on the achievement of other goals. Extensive work has assessed solutions to achieve the goals sectorally (energy security vs food security) compared with the amount of work on examining the solutions and policies to achieve the goals with an integrated approach. Our framework allows us to examine the extent to which goals can be reached simultaneously and if expansion in hydropower, irrigation, and water for domestic use is possible within the contexts of other SDG goals. Our modeling framework touches on many SDG goal dimensions: SDG2: zero hunger, SDG3: human health, SDG5: gender equality, SDG6: water access, SDG8: decent work and economic growth; SDG12: sustainable consumption and production SDG13: climate action; SDG15: life on land, and SDG17: partnerships. We find that supporting investments in agricultural development (expanding irrigated areas and increasing the productivity of rainfed cropland by reducing costs for farmers) helps basin countries toward achieving SDG2 and SDG12 goals. However, without proper regulation and environmental protection, increasing the productivity of agriculture may increase local water scarcity and deforestation, which could push SDG6 and SDG13 further out of reach. Investments to improve access to clean water and sanitation have significant economic benefits, further helping to achieve SDG6 and SDG8 but also SDG2, SDG3, and SDG5. Undernutrition and childhood stunting is made worse by chronic dehydration or exposure to water-borne pathogens, closely tying the successes of SDG6 with successes in SDG2. Universal access to clean water and sanitation in the Zambezi will also contribute significantly to SDG5, relieving women of disproportionate time burden for family water collection (Graham et al., 2016). Achieving the SDGs and basin development goals will depend on partnerships between public and private sector actors and strong cooperation and coordination among the eight basin countries through the ZAMCOM river basin organization (SDG17).

CRediT authorship contribution statement

Amanda Palazzo: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Taher Kahil:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Barbara A. Willaarts:** Conceptualization, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Peter Burek:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Michiel van Dijk:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Ting Tang:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Piotr Magnuszewski:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Petr Havlík:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Writing – review & editing, Methodology. **Simon Langan:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – review & editing. **Yoshihide Wada:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – review & editing.

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

A selection of the underlying scenario results are available on IIASA's Integrated Solutions for Water, Energy, and Land Nexus Basins Scenario Explorer: https://data.ene.iiasa.ac.at/nexus-basins/ The Community Water Mode (CWatM) is a fully open-source model and its source code is available at https://cwatm.iiasa.ac.at. The model source code is available at https://github.com/iiasa/CWatM and data to run the model are available at https://github.com/iiasa/CWatM-Earth-30min. The Global Biosphere Management Model (GLOBIOM) documentation, links to GLOBIOM resources, GAMS script descriptions and dependency links that match the main version of the GLOBIOM model are provided in a GitHub repository at https://iiasa.github.io/GLOBIOM/.https://github.com/iiasa/GLOBIOM_Prerelease_Data. Currently, GLOBIOM is shared with external partners based on bilateral agreements typically in the context of joint projects. 60+ external users/developers have access to related GitHub repositories. The Extended Continental-scale Hydroeconomic Optimization (ECHO) model is in the process of being released as open source and the model code can be made available upon request. All equations for the MARINA model are provided in the supplementary information of Wang et al. (2020). Datasets of crop yields and input requirements from EPIC have been made available through the ISIMIP 2b (for CMIP5).

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Appendix A. Supplementary data

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