

Water Use Trajectories in Agriculture and Hydropower in Zambezi River Basin: Assessing with Big Earth Data and Water-energy-food-environment Nexus Approach

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Abstract: Given the heightened competition for water in energy, food, and the environment in Africa, it is essential to implement sound integrated plans for basin or regional sustainable development. Zambezi River Basin (ZRB), one of the least developed basins in the world, is under development with great ambition for hydropower and irrigation infrastructure. Here, we proposed a framework to assess different water usage trajectories for agricultural and hydropower development scenarios with data derived from big earth data method. Three future scenarios were set for irrigation expansion and development hydropower construction according to current plan, global average and high level, respectively. Using spatial analysis methods, average evapotranspiration (ET) difference before and after irrigation expansion and reservoir construction was used to estimate water usage trajectories. Results show that the total available water resource for ZRB is estimated as 111.8 km³. Due to irrigation and reservoirs construction, additional annual water consumption is estimated to be 0.9 and 14.2 km³ for 2017, respectively. By analyzing the water-energy-food-environment (WEFE) nexus given water availability constraints, we found that the water development boundary in the ZRB could support increases in both irrigation proportion and dam density to global average levels of 20% and 0.56/10⁴ km², respectively, without degrading the environment. The proposed paradigm for assessing water resources has the potential to endow the ZRB with significant capacity to support the achievement of relevant Sustainable Development Goals (SDGs).

Keywords: water use trajectory; water-energy-food-environment (WEFE) nexus; Sustainable Development Goals (SDGs); scenarios analysis; Earth observation data; Zambezi River Basin, Africa

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1 Introduction

Since the United Nations proposed the Sustainable De-

velopment Goals (SDGs), the coordinated sustainability of resources, environment, and development has become a principle for global and regional water utilization

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(Assembly, 2015). In addition to the growing global population, the demand for water, energy, and food is substantially increasing with economic development (Albrecht et al., 2018; Zhang et al., 2018). Due to concerns about the environment resulting from over-development of water resources, a water-energy-food-environment (WEFE) perspective has emerged (Albrecht et al., 2018; Chai et al., 2020). Examples of groundwater depletion resulting from agricultural irrigation include the High Plains aquifer in the US (Scanlon et al., 2012), irrigated Indus Basins in India, the Haihe River Basin in China, and Saudi Arabia (Döll et al., 2014). The Yellow River of China has experienced zero flow downstream and in the delta region due to overuse and diversion of water upstream, as well as decreased precipitation and glacier melt caused by climate change (Di et al., 2021; Li et al., 2021). The Colorado River Basin of Argentina has experienced substantial constraints to economic development due to water scarcity resulting from competition between human and environmental demands (Wild et al., 2021). Consequently, achieving a balance between development and environmental protection under the framework of SDGs has become an essential issue for water resource management at the basin scale (Liu et al., 2017).

The nexus among water, energy, and food security was initially put forward at the Bonn 2011 conference organized by the German Federal Government (Hoff, 2011; Albrecht et al., 2018; Zhang et al., 2020). In the same year, the World Economic Forum (WEF) recognized Food-Water-Energy as one of the major global risks (WEF, 2011). Many integrated assessment models are put forward for the purpose of studying the Food-Water-Energy nexus in decision-making (Rising, 2020), such as extended continental-scale hydro-economic optimization designed for the expansion planning of water and electricity sector in Africa (Kahil et al., 2018). This model aims to optimize the allocation of water resources and the development of hydropower projects across the continent, taking into account various factors such as water availability, energy demand, and economic benefits. It provides a valuable tool for policymakers to make informed decisions on water and energy infrastructure investments. Other similar models include the Platform for Regional Integrated Modeling and Analysis (PRIMA), which investigates the nexus of climate, energy, water, and land at decision-relevant scales

(Kraucunas et al., 2015). This allows for the assessment of food and energy access, biodiversity loss, climate change, and human health under each pathway (Van Vuuren et al., 2015). These models, by integrating various aspects of the Food-Water-Energy nexus, help in identifying synergies and trade-offs, and provide a scientific basis for sustainable development strategies. Nevertheless, environmental protection priorities vary among different basins. In basins of developed regions, environmental protection and restoration are often the utmost importance. Strategies mainly center on environmental restoration (Leblanc et al., 2012; Di et al., 2021; Li et al., 2021; Wild et al., 2021), and groundwater replenishment (Scanlon et al., 2012; Döll et al., 2014). Although environmental concerns were not previously regarded as a major part of the development plans of many basins (Liechti et al., 2015), they should now be considered as an important part of the development plans in less-developed basins to maintain optimal and healthy ecosystems and prevent ecological disasters similar to those that have occurred in other basins around the world.

The Zambezi River Basin (ZRB), being Africa's fourth-largest basin remains underdeveloped (Liechti et al., 2015; Spalding-Fecher et al., 2014). Although the water stress in the ZRB is relatively minor, it has rich biodiversity, including one of the largest wetland systems in southern Africa (Beilfuss and Brown, 2010). Achieving SDG 1 (end extreme poverty) and SDG 2 (no hunger) by 2030 is crucial, necessitating development plans that balance economic growth with environmental protection through a water-energy-food-environment nexus approach. Growing demands driven by population and economic development create competition among these sectors (Palazzo et al., 2024). Water is needed for both irrigation and hydropower, while agricultural expansion can impact water quality and ecosystems. The WEFE nexus integrates these sectors to optimize resource use, minimize trade-offs, and enhance sustainability. In essence, the WEFE nexus is crucial for balancing development needs with environmental protection in the ZRB. Up to now, due to the lack of refined datasets, only a limited numbers of assessments have been carried out in the ZRB. For example, there were observed discharge data from 22 gauges, but only 5 gauges were usable after plausibility checks (Kling et al., 2014). The WEFE nexus has evolved as a crucial

framework over the past decade to address complex resource and development challenges. In our research, the WEFE nexus guided the development of the framework by integrating these interdependencies to identify synergies and minimize trade-offs. The WEFE nexus also supports stakeholder engagement and context-specific solutions, which are vital for addressing the unique challenges of the Zambezi River Basin. Our study aims to: 1) quantify the water consumption trajectory of agriculture, energy, and the environment under various scenarios; 2) analyze the WEFE nexus given water availability constraints; and 3) determine the water development boundary in the ZRB using a holistic WEFE nexus view.

2 Materials and Methods

2.1 study area

Zambezi River Basin covers an area of 1 391 305 km² and contains eight riparian countries including Zambia (42% of the whole basin), Angola (18%), Zimbabwe (16%), Mozambique (12%), Malawi (8%), Tanzania (2%), Botswana (1%), and Namibia (1%) (Fig. 1). The full length of the Zambezi River is 2574 km, which ranks fourth in Africa after the Congo, Nile, and Niger rivers (Sainz, 2018). The climate in this region is dominated by a tropical climate with only two seasons, the

dry season and the wet season. The dry season is from May to October and the wet season is from November to April of the next year. The mean annual precipitation of this region is 913.2 mm and the annual mean temperature is 22.1 °C (Sainz, 2018).

The population in the Zambezi River Basin is around 32 million, about 70% to 80% of which rely on agriculture and fishing as a livelihood (Lautze et al., 2017). Most of the eight riparian countries are suffering from severe poverty, with poverty rate varying from 18.2% to 71.4% (World Bank, 2010). Food insecurity is another urgent issue in this basin. The food-insecure population is 64.1% of the total population in Zambia, followed by 60.4% in Angola, 48.9% in Zimbabwe, 41.2% in Mozambique, and 26.8% in Malawi (Baquedano et al., 2020). Developing hydropower electricity becomes a way to improve the local economy and get rid of poverty. Now, the installed hydropower capacity in the Zambezi River Basin has reached 5000 MW and the potential capacity is estimated as 1300 MW (World Bank, 2010). Cahora Bassa, Kariba and Kafue Gorge dams generated 2075, 1470, and 990 MW of electricity, respectively (World Bank, 2010).

Overall, the ZRB has substantial opportunities for economic development through untapped hydropower potential and irrigation expansion. However, these opportunities also bring risks to the environment and lead

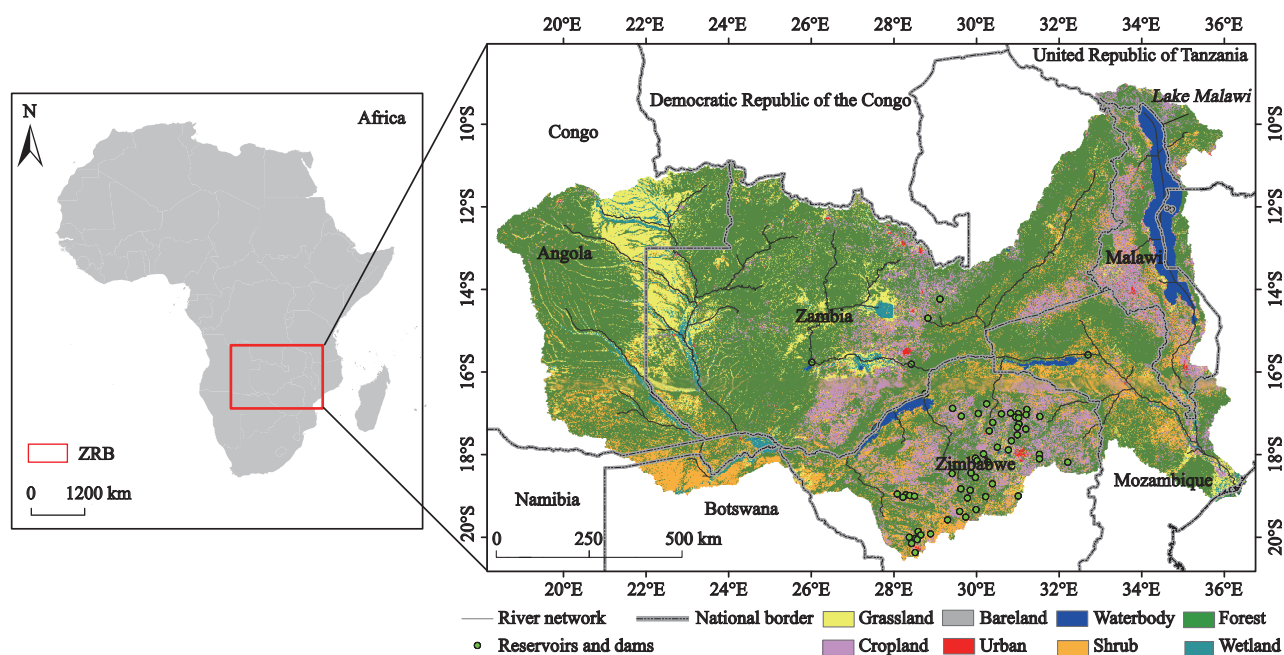


Fig. 1 Geographical location (a) and land cover of the Zambezi River Basin (ZRB) (b). Landcover product was obtained from Copernicus Global Land Service (CGLS-LC100) in 2018

to competition for water resources. The development plans for hydropower and irrigation need to consider their impacts on downstream water users, environmental flows, and land use changes.

2.2 Data

2.2.1 Precipitation, evapotranspiration, and water storage change data

This study utilized the integrated evapotranspiration (ET) data generated by Elnashar et al. (2020) to estimate the ET of rainfed cropland, irrigated cropland, and reservoirs. This data incorporates 13 types of global or regional ET datasets (Elnashar et al., 2020), such as Penman-Monteith Leuning (PML) (Zhang et al., 2019), operational Simplified Surface Energy Balance (SSE-Bop), Moderate Resolution Imaging Spectroradiometer (MODIS, MOD16A2105) (Mu et al., 2011) and the Numerical Terradynamic Simulation Group (NTSG) (Zhang et al., 2010). After validating the existing global ET dataset using flux eddy covariance data, a fused global monthly ET dataset with a spatial resolution of 1-km from 1982–2019 was synthesized. This dataset is archived on Google Earth Engine (GEE) and can be accessed through the following address: <https://elnashar.users.earthengine.app/view/synthesizedet> (cited on July 11, 2025). We validated this ET data using eddy covariance (EC) site data from November 2007 to September of 2008, which is derived from Fluxnet (<https://fluxnet.org/sites/siteinfo/ZM-Mon>). This location of this site data is at coordinates (15.4391°E, 23.2525°S), with elevation of 1053 m and landcover of deciduous broadleaf forests. The results are shown in Fig. 2. The R^2 is 0.76,

and with Root Mean Square Error (RMSE) of 7.15 mm and Mean Absolute Percentage Error (MAPE) of 9.3%. These results indicate that the evapotranspiration data basically meets the accuracy requirements for water resource management.

Precipitation (P) data used in this study is from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset, which is estimated by rain gauges and satellite observations (Funk et al., 2015). CHIRPS has been providing precipitation estimates from 1981 up to the present with a resolution of 0.05°. The CHIRPS data can be obtained from <https://data.chc.ucsb.edu/products/CHIRPS-2.0/>. CHIRPS demonstrates good consistency with on-situ measurements in Zambezi River Basin (Katsanos et al., 2016; Rivera et al., 2018).

To estimate the change in water storage (ΔS), this research utilized data from the Gravity Recovery and Climate Experiment (GRACE). By monitoring the monthly changes in the gravity field, GRACE delivers monthly estimates of the changes in groundwater, an important component in the water balance equation (Swenson et al., 2003; Schmidt et al., 2006; Felfelani et al., 2017). GRACE data are in the unit of ‘Equivalent Water Thickness’, which represents the deviations of mass in terms of the vertical extent of water in cm. This dataset is archived in the GEE platform (Gorelick et al., 2017), and comprises three layers: Lwe_thickness_csr, lwe_thickness_gfz, lwe_thickness_jpl corresponding to three level-2 products from University of Texas/Center for Space Research (CSR), GeoForschungsZentrum Potsdam (GFZ), and NASA Jet Propulsion Laboratory (JPL), respectively (Singh et al., 2023). Given minor result variations among these products, this study averaged all three, following National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory recommendations. The GRACE product used spans from 2002 to 2016 with a spatial resolution of 1°. As for the missing values in the GRACE data, we calculate the water storage change using the equivalent water level difference between January of two years. If the data for January is missing, we interpolate with the data from December or early February. The average runoff in a region is calculated using the water balance equation. Since the GRACE data is available from 2002 to 2016, and the data for 2002 is incomplete, the period from 2003 to 2016 is used as the reference period to calculate

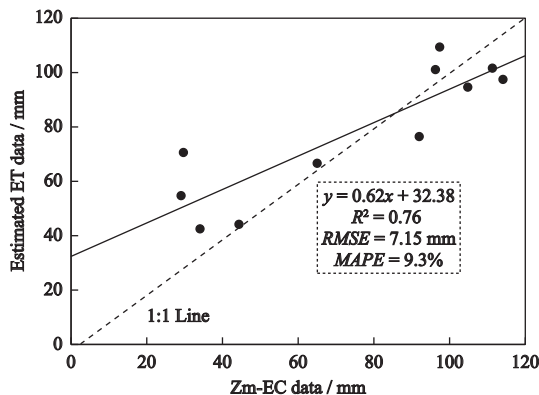


Fig. 2 Validation of synthesized data with eddy covariance (EC) site data in Zambezi River Basin (Zm-EC) (15.4391°E, 23.2525°S) from November 2007 to September of 2008. ET is evapotranspiration

the average runoff and estimate the available water resources in the basin.

2.2.2 Irrigated cropland data

The irrigated cropland map is from the Global Maximum Irrigated Extent (GMIE) dataset with a spatial resolution of 30 m (Wu et al., 2023; Tian et al., 2025). The irrigated cropland mask was used to estimate the water consumption by irrigation agriculture. Considering that little precipitation in the dry season (May to December) can barely support the crop growth in Zambezi River Basin, GMIE detected the irrigation signal using the Normalized Difference Vegetation Index (NDVI) from Landsat 8 in 2018. If the cropland NDVI exceeds a certain threshold (θ) (here, $\theta = 0.40$) (Wu et al., 2023), the pixel of the cropland is regarded as irrigated cropland. We selected 594 verification points (including 294 irrigated cropland samples and 300 rain-fed cropland samples) to verify the accuracy of irrigated cropland through visual interpretation. The verification results showed that the accuracy of this regional irrigation land data was 95.8% (Fig. 3).

In order to estimate the water consumption of each type of landcover (except cropland), this study used the landcover product of Copernicus Global Land Service (CGLS-LC100) in 2018 with a spatial resolution of 100 m (Tsensbazar et al., 2018; Xu et al., 2019). Because the CGLS-LC100 is at 100 m spatial resolution, we used the regional cropland data in 2018 in Zambezi River

Basin at 10 m spatial resolution (Bofana et al., 2020). The overall accuracy of this dataset is 84%, which can meet the accuracy requirements of water resources management in the region. To calculate the average ET for different landcover, irrigated and rain-fed cropland, we select the ‘pure pixel’ of each 1 km to match the resolution of ET data. To estimate the total amount consumed from different landcover, we use the average value multiplied by the total area to avoid the mismatching issue of resolution using data from 2015 to 2019, during which years the cropland and evapotranspiration (ET) are concentrated. This period is primarily used for estimating the evaporation caused by irrigation and reservoir construction within the basin.

2.2.3 Dams

The Global Reservoir and Dam database (GRanD) (Lehner et al., 2011) provides information on 6862 global dams and reservoirs with a storage capacity of more than 0.1 km³ (Lehner et al., 2011), which could be accessed freely via: <https://ln.sync.com/dl/ebe25d8d0/difn4ctu-q5gpjc4m-kqjt84bu-tu6da7q5> (accessed date: March 12, 2025). The area of the reservoir is used to estimate the water consumption of hydropower. According to GRanD, the Zambezi River Basin now possesses 60 reservoirs (Fig. 1), among which the Kariba Reservoir is the largest in the basin which was built in 1961 at the national boundary of Zambia and Zimbabwe. Its maximum capacity is $191.0 \times 10^9 \text{ m}^3$ and its minimum

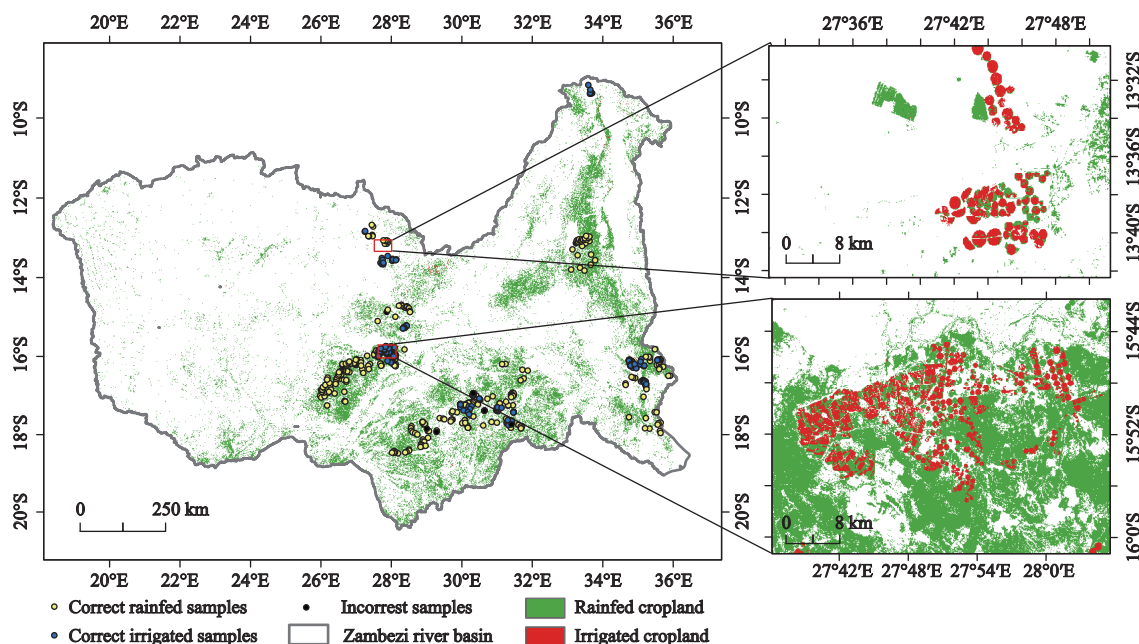


Fig. 3 Irrigated and rainfed cropland in the Zambezi River Basin in 2018

capacity is $116.0 \times 10^9 \text{ m}^3$. The Cahora Bassa Reservoir is the second-largest reservoir in the basin. It was built in 1974 in Mozambique, with a maximum capacity of $63.0 \times 10^9 \text{ m}^3$ and a minimum capacity of $12.2 \times 10^9 \text{ m}^3$ (Liechti et al., 2015).

2.3 Methods

The overall framework of this study is shown in Fig. 4. First, the annual runoff of the Zambezi River Basin is estimated using the water balance model and is considered as available water that can be used in agriculture, hydropower, and environmental sectors. Under the constraints of available water resources, we consider the future development scenarios of food, energy, and environment in different scenarios under this framework, which is related to irrigation expansion, hydropower development and environment protection, respectively. With earth observation data, the global water appropriation was estimated using overlay analysis method (Wu et al., 2022).

2.3.1 Scenarios development for irrigation

I-scenario 0: Currently irrigated cropland is the baseline of irrigation expansion scenarios. According to the GMIE dataset, the irrigated cropland area was 3729.3 km² in 2018, accounting for 1.8% of total cropland in 2015–2019.

I-scenario 1: In this scenario we consider the irriga-

tion expansion according to identified irrigation projects. According to the World Bank, ~100 irrigation expansion projects were identified from various sources in the Zambezi River Basin. The additional equipped irrigation area was 3360.0 km² in the identified irrigation expansion projects (World Bank, 2010). The identified irrigation project for each country was shown in Table S1.

I-scenario 2: Irrigation proportion reached the global average, which is about 20% according to the new global irrigated cropland map (Meier et al., 2018). In this case, the target irrigated area is about 40 953.1 km².

I-scenario 3: If the irrigation proportion reaches the highest level like that in developing countries, represented by Pakistan, which has an irrigation ratio of 53.2% (World Bank, 2019). Hence, the target irrigated area is about 108 935.2 km².

The increased water consumption due to irrigation expansion can be calculated based on Eq. (1) using irrigation area in each emigration expansion scenario and assuming that irrigation ET can be estimated with the difference between irrigated ET and rainfed ET. This method was also used in global water appropriation estimation (Wu et al., 2022) to estimate irrigation water consumption.

$$AWC_{\text{irri_inc}} = (A_{2030} - A_c) \times (ET_{\text{irri}} - ET_{\text{rf}}) \quad (1)$$

where $AWC_{\text{irri_inc}}$ is additional water consumption due

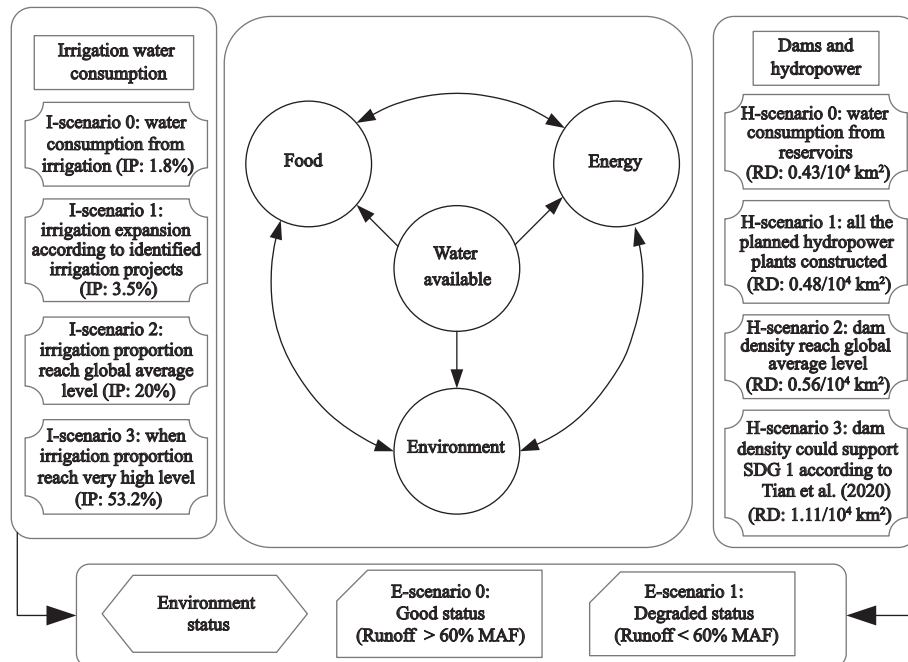


Fig. 4 Overall flow chart of scenario analysis in this research. IP represents irrigation percentage, while RD means reservoirs density. MAF means mean annual flow

to irrigation expansion in the future, which can be estimated by the increased area and increased ET . A_{2030} is irrigated area in 2030, A_c is current irrigated crop area. The difference between A_{2030} and A_c is increased irrigated area. ET_{irri} is mean ET from irrigated cropland, ET_{rf} is the mean ET in rainfed cropland. The difference between ET_{irri} and ET_{rf} is increased ET due to irrigation expansion.

2.3.2 Scenario development for dams and hydropower

H-scenario 0: Hydropower and reservoir construction will increase the area of water bodies and increase the water loss from ET as well. This scenario is the baseline for hydropower development. According to GRanD, the Zambezi River Basin now possesses 60 reservoirs. The top-10 reservoirs were listed in Table S2.

H-scenario 1: Table 1 summarizes the planned dams and hydropower plants by 2030 in Zambezi River Basin. For example, the Mozambican government plans to build a 1000 MW hydroelectric power plant along the Zambezi River in Chemba, Sofala Province, Mozambique.

H-scenario 2: Density of dams and reservoirs in this region reaches the global average level. There is a total of 60 reservoirs and dams recorded in the GRanD database for the Zambezi River Basin, while 6862 dams were recorded for the whole world. The reservoir density in this region is $0.43/10^4 \text{ km}^2$, while the reservoir density is $0.56/10^4 \text{ km}^2$ globally (Lehner et al., 2011). This scenario means there will be 0.56 reservoirs serving 1000 km^2 of land from irrigation, hydroelectricity for average.

H-scenario 3: Density of dams could support eradicating poverty. Reservoirs and hydropower plants are important infrastructures to improve water use efficiency and hydro-energy utilization. According to (Tian et al.,

2020), dams and reservoir density is also related to the poverty rate. Totally, 83.8% of countries with dams or reservoir densities larger than $1.11/10^4 \text{ km}^2$, the national poverty rate is usually lower than 4.9%. In this scenario, we consider the water consumption when dams or reservoir density is larger than $1.11/10^4 \text{ km}^2$, which indicates that 1.11 dams and reservoirs serve 1000 km^2 of land for irrigation, hydroelectricity on average.

Therefore, the increased hydropower water consumption in 2030 can be calculated based on Eq. (2) using the summed area of planned hydropower plants (2417.5 km^2) and assuming the ET over reservoirs does not change over time.

$$AWC_{res_inc} = (A_{2030} - A_c) \times (ET_{rs} - ET_a) \quad (2)$$

where AWC_{res_inc} is additional water consumption from reservoirs in the future, which can be estimated by the increased area and increased ET . The difference between A_{2030} and A_c is increased reservoir area. ET_{rs} is the mean ET from reservoir, ET_a is the mean ET in the whole Zambezi River Basin. The difference between ET_{rs} and ET_a is the increased ET due to the transformation of other landcover to the water body in the reservoir.

2.3.3 Scenario development for environmental flow

Environmental flow is the demand for water by the ecosystem. According to Tennant method (Liu et al., 2017), some researchers assess the environment flow requirement by assuming a certain percentage of mean annual flow, which ranges from 80% to a specific proportion in different basins (Liu et al., 2017). In the Zambezi River Basin, the environmental flow requirement is set as 60% of mean annual flow (MAF) as used by World Bank (2010) and Brown and Matlock (2011). If the runoff is less than 60% of MAF, the environment will degrade. So, the maximum available water is 40% of MAF under

Table 1 Summary of planned dams and hydropower plants by 2030 in Zambezi River Basin

Planned hydropower plants	Source	Commissioning year	Turbine capacity planned / MW	Area / km^2
Kafue Gorge (lower)	Liechti et al., 2015; Spalding-Fecher et al., 2014	2017–2022	750	1.5
Batoka Gorge	Liechti et al., 2015; Spalding-Fecher et al., 2014	2023–2024	1600	26.0
Mphenda Nkuwa	Liechti et al., 2015; Spalding-Fecher et al., 2014	2024	1500	100.0
Kholombidzo	Liechti et al., 2015; Spalding-Fecher et al., 2014	2025	240	152.0
Devil's Gorge	Spalding-Fecher et al., 2014; Spalding-Fecher et al., 2016	2028	1240	710.0
Kabompo Gorge	Spalding-Fecher et al., 2014	–	34	28.0
Chemba	Spalding-Fecher et al., 2014	–	1040	1400.0
Total	–	–	6404	2417.5

the constraint of keeping the good status of the environment.

In this study, the MAF is calculated as the average annual runoff from 2003 to 2016 due to the availability of GRACE data. The annual runoff (R) can be computed based on the water balance model (Eq. (3)).

$$R = P - ET - \Delta S \quad (3)$$

where P is the precipitation from the CHIRPS dataset, ET is the evapotranspiration from integrated ET data generated by Elnashar et al. (2020), and ΔS is water storage change. The amount of MAF (e.g., 60% of MAF in this study) that is required to maintain the proper operation of the ecosystem can be determined. The rest of the MAF (e.g., 40%) is the water available to support agricultural irrigation and hydropower generation.

So, there will be two scenarios after considering the water consumption from agriculture and hydropower. **E-scenario 0:** the environmental condition keeps good status or the runoff is larger than 60% of MAF. **E-scenario 1** will be the degraded status or the runoff of less than 60% of MAF.

3 Results

3.1 Water consumption for each sector

The distribution of precipitation in the Zambezi River Basin is shown in Fig. 5a. The precipitation decreases from north to south, and the total amount of water gained from precipitation during 2003–2016 was 1295.45 km³. Fig. 5b shows the spatial distribution of ET, and the highest value of ET is observed in the open water area (lakes and rivers). According to GRACE data, the equivalent water level between 2003 and 2016 increased by 5.82 mm, which is equivalent to an increase in water storage of 8.11 km³ (Fig. 5c). Spatially, except for the decreased water storage in the northeast of the basin (Lake Malawi region), water storage in other regions showed positive changes. According to Eq. (1), the MAF of the Zambezi River Basin is estimated to be 111.8 km³ (Fig. 5d), which is similar to the previous study (105–108 km³) (Hejazi et al., 2014; Spalding-Fecher et al., 2014). The standard deviation of annual runoff during 2003–2016 is 29.6 km³, so the available water will range from 82.2 km³ in the dry year to 141.4 km³ in a wet year.

Differ from previous time span of annual runoff ana-

lysis, which is from 2003 to 2016, a relatively short period from 2015 to 2019 was chosen to analyze the water consumption of different land cover types. The primary reason for choosing this period is that it covers the most recent five years of available data, allowing for a more up-to-date assessment of water consumption patterns. Fig. 5e shows the average annual ET from 2015 to 2019 of each landcover type in the Zambezi River Basin. The reservoir has the highest average ET among all, reaching 1799.4 mm, followed by open water (reservoirs and lakes, 1495.9 mm), wetland (1046.6 mm), irrigated cropland (927.9 mm), and forest (868.4 mm), which all show above-average annual ET. While that of rainfed cropland, shrubs, grasslands, and urban present below-average annual ET. In terms of total water consumption (Fig. 5f), the forest ranks first with 65.2% of the total water consumption by all landcovers, followed by cropland which consumed 9.7% of the total water consumption. The irrigated cropland accounts for only 3.1% of water consumption by cropland, while the rest 96.9% is attributed to rainfed cropland. Compared with open water, the water consumption of reservoirs only takes a small proportion, which is mainly due to the smaller total area of the reservoirs.

3.2 Water consumption under different irrigation scenarios

The total cropland area in the Zambezi River Basin is estimated to be 204 765.7 km², of which 1.8% is irrigated cropland (3729.3 km²) (Wu et al., 2023; Tian et al., 2025). Using spatial analysis methods to calculate the average ET (evapotranspiration) of irrigated cropland and rainfed cropland, the difference between the two is regarded as the increased water consumption caused by irrigation. This method has been successfully applied to the global assessment of agricultural water consumption (Wu et al., 2022). The average ET of rain-fed cropland is 686.2 mm, and the average ET of irrigated cropland is 927.9 mm, which indicates irrigation may lead to an increase of ET of about 241.7 mm (Fig. 5e). The extra ET of 241.7 mm was used to calculate the additional water consumption due to irrigation. The water consumption for three scenarios was listed in Table 2.

I-scenario 0: Water consumption at the current stage. The water consumption of irrigated cropland was estimated as 0.9 km³ (= 241.7 mm × 3729.3 km²) at the current stage.

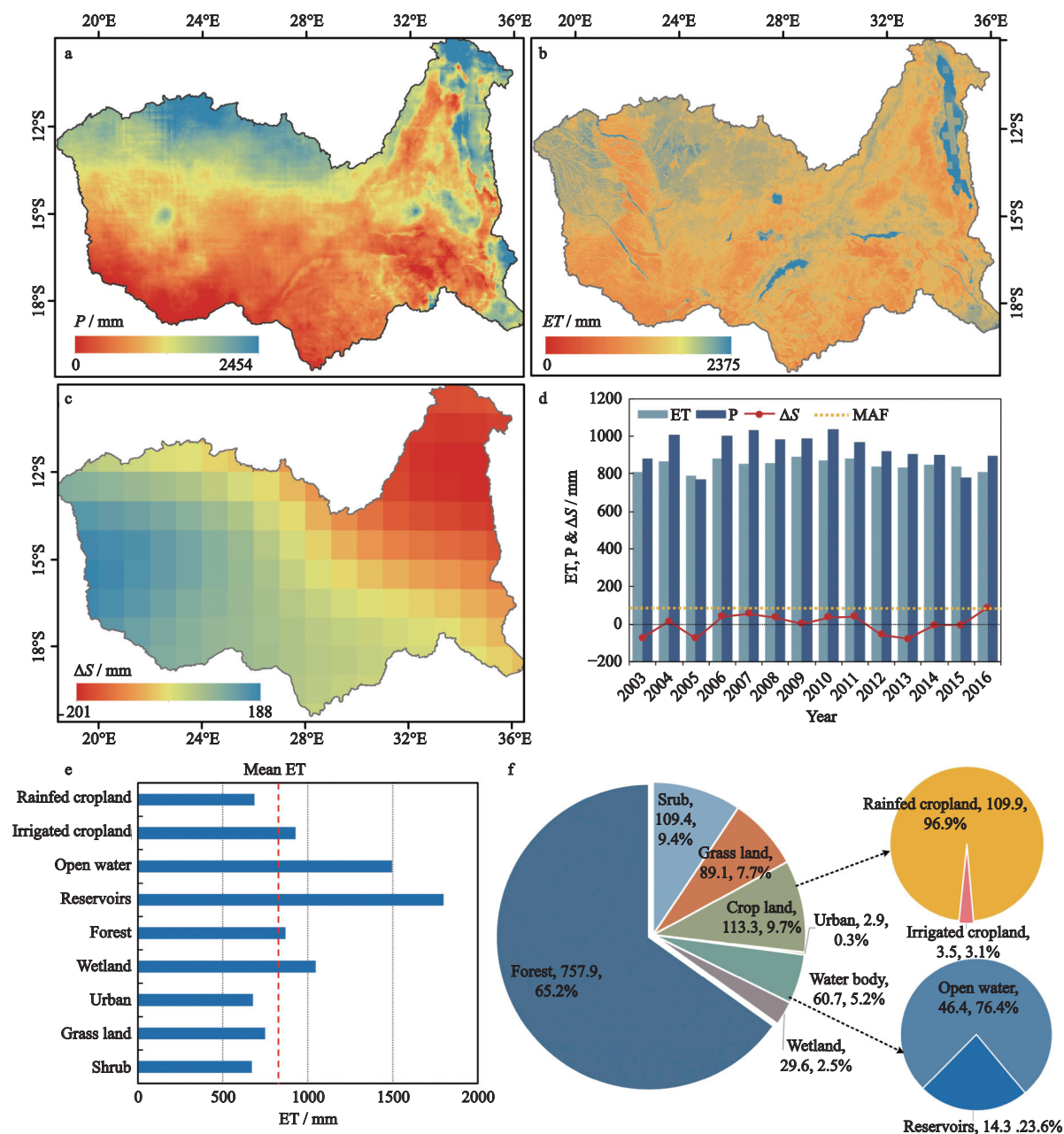


Fig. 5 Spatial distribution of mean precipitation (P) (a), evapotranspiration (ET) (b) and the change of water storage (ΔS , represented by equivalent water level here in mm) during 2003–2016 (c), and their temporal trend (d). e is average ET of land covers from 2015 to 2019 and f is total water consumption of each type of land cover in amount (km³) and proportion (%). MAF: mean annual flow

I-scenario 1: Water consumption after irrigation expansion according to identified projects. The identified irrigation project for each country was shown in Table S1. The additional equipped irrigation area was 3360.0 km² in identified irrigation expansion projects (World Bank, 2010). In this scenario, the irrigation water consumption will increase by 0.8 km³, accounting for 0.7% of MAF, leading to 1.7 km³ of total water consumption due to irrigation.

Irrigation water consumption under I-scenario 2. If the irrigation ratio reaches 20% at the global level, the irrigated cropland should increase to 40 953.15 km² accordingly, and the corresponding irrigation water consumption will increase from 0.9 to 9.9 km³.

Irrigation water consumption under I-scenario 3. If the irrigation proportion reaches the high-level like in developing countries, represented by Pakistan (53.2% according to World Bank, 2019). Hence, the target irrig-

Table 2 Irrigated water demand under different scenarios in Zambezi River Basin

Scenarios	I-scenario 0	I-scenario 1	I-scenario 2	I-scenario 3
Irrigation percentage / %	1.8	3.5	20.0	53.2
Irrigated area / km ²	3729.3	7089.3	40953.1	108935.2
Additional water consumption / km ³	–	0.8	9.0	25.4
Percentage of MAF / %	–	0.7	8.0	16.7
Water consumption for irrigation / km ³	0.9	1.7	9.9	26.3

ated area is about 108 935.2 km². The corresponding irrigation water consumption will increase from 0.9 to 26.3 km³, which means this will consume additional 18.7 km³.

3.3 Water consumption under different hydropower development scenarios

The average ET of the Zambezi River Basin is 844.9 mm, while the ET of the reservoir is 1799.4 mm from 2015–2019 (Fig. 5e). So, this indicates that the construction of the new reservoir, which results in an expansion of the water surface area, will lead to an increase in evapotranspiration (ET) by 954.5 mm. So, we will use this value to estimate additional water consumption caused by reservoir construction.

H-scenario 0: Currently, the total area of 60 existing reservoirs in the Zambezi basin is about 7957.3 km². The total water consumption of reservoirs at the current stage is estimated as 14.2 km³, accounting for 23.4% of the total water consumption of open water bodies (reservoirs and lakes). Table S2 lists the water consumption of the top 10 largest reservoirs within the basin. The largest consumption is observed at Kariba, which is 9.39 km³/yr, accounting for 65.8% of the water consumption of all 60 reservoirs. The water consumption of the Cahora Bassa reservoir comes second with 3.64 km³/yr (Table S2).

H-scenario 1: Considering seven more reservoirs would be built by 2030 (Table 1), the construction and expansion of hydropower plants make the total area of hydropower increase to 10 374.8 km², which accordingly raises the reservoir water consumption to 18.7 km³ by 2030. The increased water consumption is 2.3 km³ compared with 2020, which equals 2.1% of MAF.

H-Scenario 2: When the dam and reservoir density reach the global average level of 0.56/10⁴ km² (Lehner et al., 2011), 17 reservoirs or dams should be constructed. The average area of each reservoir was 154.8 km² according to existing and planned reservoirs. Assuming that the mean area of additional reservoirs is the same as existing and planned reservoirs. So, the total reservoir area should be 119 23.5 km², indicating that total water consumption from reservoirs will reach 21.2 km³/yr (Table 3). In this scenario, additional 3.7 km³ water will be consumed by reservoirs, which accounts for 3.3% of MAF.

H-Scenario 3: According to (Tian et al., 2020), reservoir density is also related to the poverty rate. In 83.8% of countries with a reservoir density large than 1.11/10⁴ km², the national poverty rate is usually lower than 4.9%. This scenario means there will be 1.11 reservoirs serving 1000 km² of land from irrigation, hydroelectricity on average. The reservoir area will reach 24 001.4 km² with total water consumption of 42.7 km³ (Table 3). Additional 15.0 km³ of water or 13.4% of MAF will be consumed during the conversion from another surface to open water.

3.4 Environmental flow assessment under different scenarios

After considering water consumption from agriculture and hydropower, there are two scenarios: E-scenario 0 (good environmental status or runoff > 60% of MAF) and E-scenario 1 (degraded status or runoff < 60% of

Table 3 Water demand from hydropower development in different scenarios

Dam density	Present / (0.43/10 ⁴ km ²)	2030 / (0.48/10 ⁴ km ²)	Global average / (0.56/10 ⁴ km ²)	Supporting no poverty / (1.11/10 ⁴ km ²)
Number of reservoirs and dams	60	67	77	155
Mean area for each reservoir / km ²	132.62	154.85	154.85	154.85
Total reservoir area / km ²	7957.3	10374.8	11923.3	24001.4
Total water consumption / km ³	14.2	18.5	21.2	42.7
Additional water consumption / km ³	–	2.3	3.7	15.0
Percentage of MAF / %	–	2.0	3.3	13.4

MAF). In E-scenario 0, the environmental condition keeps good status or the runoff is larger than 60% of MAF or 67.1 km^3 . In this scenario, the remaining 40% or MAF or 44.7 km^3 is the amount of water available. Otherwise, E-scenario 1 will be the degraded status or the runoff is less than 60% of MAF or 67.1 km^3 . Given the total available water will reduce by 29.6 km^3 in a dry year, the minimum water requirement of ecosystem will be 15.1 km^3 ($44.7 - 29.6 \text{ km}^3$) in the dry year. The interannual changes in available water also will be treated as important factors for different development scenarios.

3.5 Water use trajectories in Zambezi River Basin

At present, the total water consumption of agricultural irrigation (0.9 km^3 , Table 2) and hydropower (14.2 km^3 , Table 3) is 15.1 km^3 . Fig. 6 illustrates the combination of water consumption of irrigated agriculture and hydropower under different scenarios. The total water use for the combination of the current development plan (H-scenario 1 and I-scenario 1) amounts to 3.1 km^3 . Under the global average condition (H-scenario 2 and I-scenario 2), the total water use is 12.7 km^3 . Meanwhile, the total water use for the combination of high-level scenarios around the world (H-scenario 3 and I-scenario 3) is projected to increase significantly to 40.4 km^3 . As for the general (average) condition, available water could

afford all the development of scenarios except the combinations with H-scenario 3 and I-scenario 3. However, for some extremely dry years, the rest flow can not meet the demand of the environment, such as the combination of H-scenario 3 and I-scenario 3 with all other scenarios. So, the optimal combination of development scenarios is the combination of H-scenario 2 and I-scenario 2 or the irrigation proportion and dam density reaching the global average level.

4 Discussion

4.1 Support of data derived from Earth observation for WEFE assessment

The ground data are very scarce in ZRB due to limited investment (Wu et al., 2020). Only a few gauge stations established in the area (Liechti et al., 2012; Kling et al., 2014; Sainz, 2018). The temperature data is only available from 10 stations across the entire ZRB basin up to 2018, which spans approximately $1.39 \times 10^6 \text{ km}^2$. Moreover, the quality of the site-based data is highly uncertain because the values from the same gauge station may differ among different providers (Sainz, 2018). The data derived from Earth observation could provide sufficient information about water and agriculture status (Wu et al., 2021). Evapotranspiration is the cardinal component in the hydrological process (Wu et al., 2022). With the support of accurate ET data, we proposed a new paradigm to assess the water resource with data derived from Earth observation rather than a complicated hydrological model. In this paradigm, the consumptive water use by irrigated agriculture and evaporation loss from reservoirs are quantified (Wu et al., 2022)

In this study, the irrigation water consumption at the current stage is estimated to be 0.9 km^3 using global comprehensive ET data and the area of irrigated cropland (Table 2). According to Tethys model, an open-source spatiotemporal downscaling model for global water demand (Li et al., 2018), irrigation water withdrawal was 2.7 km^3 in 2015 in ZRB. Considering that the irrigation efficiency in this area is about 0.30 according to the Food and Agriculture Organization of the United Nations' (FAO) Global Information System on Water and Agriculture (AQUASTAT) database (<https://data.apps.fao.org/aquastat/?lang=en>) in 2015, irrigation water consumption could be estimated as 0.81 km^3 , which is close to the value of 0.9 km^3 in this study. Ac-

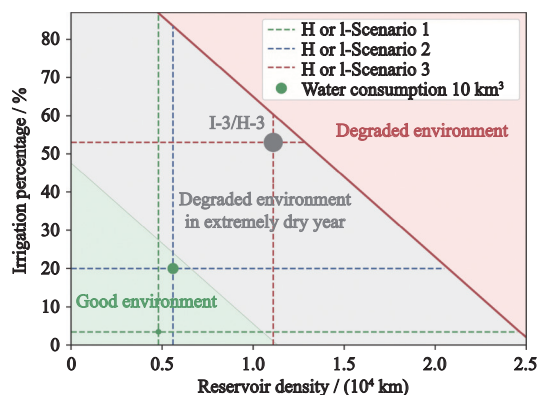


Fig. 6 Relationship between reservoir density and irrigation percentage under scenario combinations. The red line is the boundary of environment status. Horizontal lines (green, blue, red): irrigation water use. Vertical lines (green, blue, red): reservoir water use. Three dots mean three scenarios of water use: I-1/H-1, I-2/H-2, and I-3/H-3 combinations. Intersections: total water use. The areas are color-coded to indicate different environmental conditions: green represents a good environment, grey signifies a degraded environment in an extremely dry year, and red denotes a degraded environment

cording to our result, the annual runoff of the basin is 111.83 km³, which is very close to the 105–113 km³ in other studies from hydrological models (Hejazi et al., 2014; Kling et al., 2014; Spalding-Fecher et al., 2014). All of these consistent results basically confirmed the reliability of earth observation data in monitoring water consumptions.

However, when using evapotranspiration (ET) data, precipitation data, and GRACE satellite data from different sources, several factors can affect the accuracy of the final results. Each dataset may contain its own measurement errors or uncertainties. For example, ET data might be influenced by the accuracy of the sensors or models used. Precipitation data could have spatial and temporal inaccuracies, while GRACE data might be affected by noise or limitations in spatial resolution. Combining data from different sources often leads to compatibility challenges. Differences in spatial resolution, temporal frequency, and data processing methods can create inconsistencies when integrating these datasets. The models used to analyze these data often rely on parameters that may not be precisely known. Uncertainty in these parameters can propagate through the analysis, affecting the reliability of the results.

4.2 Assessment of water-energy-food-environment nexus for achieving SDGs

The trade-off between food and energy is assessed under the constraint of water resources. Besides food, energy, and water, the target of environmental protection as the fourth factor is incorporated in this framework. In previous research, they rarely consider environmental protection as a whole, which is vital for ZRB due to the ZRB supports many unique species in the region (Beilfuss and Brown, 2010). Water resource being one of the key factors in the WEF nexus (Hoff, 2011) especially in Africa.

Hydropower is a type of clean and cheap energy, and one of the main energy sources in the Zambezi River Basin. In Mozambique, 94% of the country's energy supply comes from hydropower (<https://www.hydropower.org/country-profiles/mozambique>). About 15×10^6 people in Mozambique still have no access to electricity, most of whom are located in rural and northern regions. Therefore, hydropower development in this region is essential to ensure social development and eradicate poverty (Tian et al., 2020). The relationship between hy-

dropower and economic development is not our area of focus in this paper. However, it is important to note that more research is needed to explore the feasibility of hydropower development. Specifically, future studies could address the complex interplay between economic benefits, social impacts, and environmental sustainability. This includes conducting comprehensive site-specific assessments, evaluating long-term environmental impacts, and engaging with local communities to ensure that hydropower projects are both viable and socially acceptable.

Expanding irrigation is one of the effective measures to strengthen food security in the region. Previous studies have revealed that Sub-Saharan Africa may be one of the regions with huge irrigation potential in the world (Dubois, 2011; Tian et al., 2022). Our results also confirmed this point, that the water resources in this area can support the expansion of irrigated land in different scenarios (Fig. 6). Considering that the irrigated arable land accounts for about 20% of global arable land, but contributes about 40% of global food production (Droogers et al., 2010; Salmon et al., 2015; Brocca et al., 2018), the average yield of irrigated cropland is 2.67 times that of rain-fed cropland. When the irrigation proportion reaches 20% in the study area, the food production will increase by 29.1% for the whole basin, which will eliminate the food gap between the current status and the 'no hunger' target. Compared with the global average crop yield, the rainy season crop yield in this area is extremely low. Taking corn as an example, according to the grid crop yield data in 2016 (Müller et al., 2019), the crop yield in this basin is 1.45 t/ha and is far below the global average (5.14 t/ha), even with a 29.1% increase (1.87 t/ha) (Tian et al., 2022). The increase in yield due to irrigation could significantly improve food situation in ZRB.

4.3 Perspective on irrigation and hydropower development

The WEF nexus approach offers several advantages for the ZRB. It provides a holistic framework to assess the interdependencies among water, energy, food, and the environment, enabling more sustainable development planning. This approach helps identify optimal development scenarios that balance economic growth with environmental protection, such as expanding irrigation and hydropower while maintaining ecological health.

We proposed an open framework to assess the water competition between food, energy, and the environment. We could introduce more indicators in this integrated system under the scenario analysis.

In this research, we did not consider the effect of climate change, because climate change is more related to the long-term (e.g., multiple decades) change of climate indicators. Base on the NASA Earth Exchange Global Daily Downscaled Projections (NASA NEX-GDDP) dataset (<https://registry.opendata.aws/nex-gddp-cmip6/>), the annual maximum temperature is projected to significantly increase by 2050 (Fig. 7a), while precipitation is not expected to exhibit a significant trend under the RCP8.5 scenario (Representative Concentration Pathway, very high emission scenario) (Fig. 7b). This aligns with the consensus among most scholars that the region will become warmer, which will increase water vapor content (Bates et al., 2008; Beck and Bernauer, 2011; Spalding-Fecher et al., 2014; Stanzel and Kling, 2014). Under a drying climate, hydropower generation is estimated to reduce by 6% in 2050 in the Lower Zambezi River Basin (Stanzel and Kling, 2014) and the hydropower production potential will decrease by 9% in the 2020s, 18% in the 2050s, and 28% in the 2080s (Hamududu and Killingtveit, 2016). Also, warmer and drier conditions will cause an increase in water consumption from irrigated cropland and reservoir's open water body, which will reduce water availability for the environment and exacerbate water competition between agriculture and hydropower development. Overall, the tendency of getting warmer and drier in this region may reduce available water in ZRB. However, even in the worse RCP of RCP8.5, the temperature is projected to

increase by 1.16 °C. So, the effect of getting warmer on available water will be under control by taking measures of reducing emissions.

5 Conclusions

The balance of development and environment under the framework of SDGs is a key issue for modern basin development. ZRB, the least developed basin in the world, and rich in biodiversity, is selected as a study area to investigate development scenarios. Based on Earth observation data, we estimated total available water resource of 111.8 km³ from 2003 to 2016 in study area. MAF with 60% is required for the normal operation of ecosystems, and the remaining 40% of MAF or 44.7 km³ is the amount of water available for agricultural irrigation and hydropower development. From 2015 to 2017, the water consumption is 15.1 km³ from both irrigation and hydropower. We assessed water consumption in different scenarios in the future based on the data from 2015 to 2019. Three future scenarios were set for irrigation expansion and hydropower development according to: 1) the identified plan, 2) the global average level, and 3) high level around the world. Using spatial analysis methods, average ET difference before and after irrigation expansion and reservoir construction was used as additional water consumption. We found that the water resources in the ZRB could support increases in both irrigation proportion and dam density to global average levels of 20% (I-scenario 2) and 0.56/10⁴ km² (H-scenario-2), respectively, without degrading the environment. For further applications, the WEFE nexus framework can be adapted to other river basins facing similar

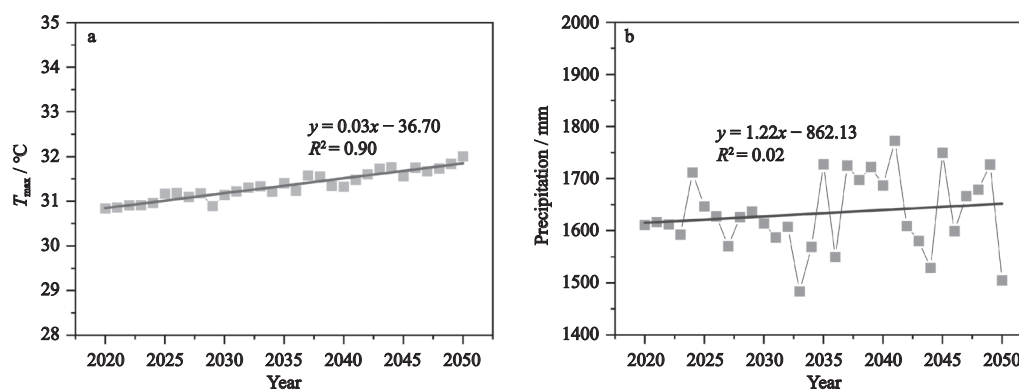


Fig. 7 The projected annual maximum temperature (a) and precipitation (b) according to in RCP8.5 according to the National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NASA NEX-GDDP) dataset in Zambezi River Basin from 2020 to 2050

challenges. The framework supports the integration of stakeholder perspectives and can guide policy-making towards achieving Sustainable Development Goals (SDGs) in the region.

Supplementary

Tables S1 and S2 could be found at <http://egeoscienc.neigae.ac.cn>.

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Conflict of Interest

The authors have no financial or proprietary interests in any material discussed in this article.

Author Contributions

TIAN Fuyou proposed the idea for data curation, formal analysis, methodology, and writing-original draft; ZENG Hongwei contributed to the idea, the data curation, and writing. WU Bingfang contributed to funding acquisition, project administration, and final reviewing; ZHANG Miao, ZHU Weiwei, Elijah PHIRI, Emmanuel MASHONJOWA polished this paper.

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