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The state of the water-energy-food nexus at sub-national scales in southern Africa: the case of South Africa and Zimbabwe

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Despite repeated commitments to universal access to water, energy, and food, most developing countries continue to face challenges to the security of these strategic resources and struggle to achieve the related Sustainable Development Goals (SDGs 2, 6, 7). We assessed the state of the water-energy-food (WEF) nexus at sub-national scales in South Africa (Inkomati Usuthu Water Management Area) and Zimbabwe (Mzingwane Catchment), employing a mixed-methods approach that included (i) a literature review, (ii) stakeholder engagement, (iii) observations and (iv) modelling. The key inputs in the iWEF tool were pairwise comparison matrices (PCMs) developed from key WEF-related expert stakeholders' pairwise judgements of the six iWEF model indicators. Inkomati Usuthu Water Management Area and Mzingwane Catchment had WEF nexus composite indices of 0.209 and 0.189, respectively, indicating that the management of WEF resources is moderately sustainable. The irregular shape of the centrepieces in the spider diagram in the iWEF tool is symptomatic of an overall imbalance in the management of WEF resources in the Inkomati Usuthu Water Management Area and the Mzingwane Catchment. These findings provide entry points for prioritised interventions to improve resource security. Still, these should be planned and implemented from a nexus perspective to optimise synergies and minimise trade-offs and risks. With the two case studies located in arid and water-scarce regions, opportunities for improving WEF security lie in managing available resources from a nexus perspective. Decentralised and off-grid solutions should also be considered, especially in rural areas where most of the population lives in the Inkomati Usuthu Water Management Area and the Mzingwane Catchment. To conclude, southern African countries share a similar history, context, and WEF-related developmental challenges. It can be inferred that their sub-national scales are in moderately sustainable states of the WEF nexus, which require nexus planning for integrated, contextualised solutions to improve collective WEF security for all.

KEYWORDS
global south, iWEF, resource security, sub-national scale, sustainable development, water-energy-food nexus model

1 Introduction

Water, energy, food and land resources are fundamentals for socio-ecological integrity and dignity, economic prosperity, livelihoods, and sustainable development (Amer et al., 2017; Leal Filho et al., 2018). The availability and sustainability of these strategic resources heavily rely on nature, ecosystem health and environmental integrity (Hoff, 2011; Carmona-Moreno et al., 2021; Jain et al., 2023). Governments elsewhere and in southern Africa, including South Africa and Zimbabwe, are committed to ensuring resource security for all, including universal access to water, energy and food, through the UN Agenda 2030 for Sustainable Development (UNGA, 2015), and their regional and national policy frameworks, including constitutions (GoSA, 1996; GoZ, 2023b). However, climate change and the continued environmental degradation and depletion of resources, among other challenges, threaten southern African countries' ability to safeguard resource security for all and achieve the Sustainable Development Goals (SDGs; ZimStat, 2023a; Sachs et al., 2025; StatsSA, 2025; UN, 2025b). This is evidenced by the persistent (i) insecurity of strategic resources, including water, energy and food (ZimStat, 2023a; StatsSA, 2025), (ii) suboptimal progress in the achievement of SDGs (Sachs et al., 2025), (iii) breaching of the majority of the nine planetary boundaries (Planetary Boundaries Science (PBScience), 2025). The breached planetary boundaries include those related to water, energy, food and land, especially those for climate change, biosphere, land system, freshwater, and biogeochemical flows (Planetary Boundaries Science (PBScience), 2025).

Out of all 16 Member States of the Southern African Development Community (SADC), only Mauritius has a 2025 SDG Index Score (70.3; ranked 76th out of 162 globally) that is higher than the world score of 68.6 (Sachs et al., 2025). The remaining 15 SADC Member States, including South Africa (2025 SDG Index Score: 64.1; Global Rank: 111th) and Zimbabwe (2025 SDG Index Score: 57.4; Global Rank: 137th), all fall in the lower one-third of the recorded 162 countries (Sachs et al., 2025). Although there is some notable progress in some SDGs in the region, the current trends project likely failure to achieve all the SDGs by 2030 (AU, AfDB, UNDP and UNECA, 2025). The majority of SADC Member States continue to face challenges and experience suboptimal progress in majority of the SDGs including those for food (SDG 2—zero hunger), water (SDG 6—clean water and sanitation), energy (SDG 7—affordable and clean energy), climate (SDG 13—climate action) and land (SDG 15—life on land; Sachs et al., 2025).

The multiple biophysical and socioeconomic challenges to universal resource security and the achievement of the SDGs in the SADC region and beyond are complicated and compounded by unilateral and siloed policies and unaligned strategies (Mabhaudhi et al., 2018; Nerini et al., 2024; Sachs et al., 2025). In the SADC region, member state governments are typically structured in a functional and sectoral manner that tends to reinforce silos, rather than supporting collaboration, integration, and coordination. These challenges are also evident at the continental and regional levels (Kabeya et al., 2022; SADC, 2023). The silo mentality, characterised by adherence to vertical divisions and horizontal functions, causes fragmentation of institutions and policy incoherence, hinders cross-sectoral collaboration, overlooks cross-sectoral co-benefits, and ultimately undermines efficient resource use, integrated climate action, and sustainable development (de Waal et al., 2019; Lah, 2025). Addressing these interconnected challenges across the interdependent resources and sectors and sustainable development pillars/dimensions, goals and sub-goals/targets for accelerated achievement of commitments requires transformative approaches such as integrated nexus planning (Javan et al., 2024; Nerini et al., 2024; AU, AfDB, UNDP and UNECA, 2025; Sachs et al., 2025; UN, 2025a). For example, to address institutional silos across water, energy and food sectors, SADC developed a regional water-energy-food (WEF) nexus governance framework whose key components include cross-sectoral mechanisms such as the joint Working Group, Technical Committee, and Ministerial Committee (Jembere, 2021; Kabeya et al., 2022).

Strategic sectors such as water, energy, food and natural resources that underpin their security are interconnected and interdependent in a water-energy-food (WEF) nexus such that actions in one sector influence outcomes in the other sectors, either beneficially (synergies) or adversely (trade-offs; Hoff, 2011; Carmona-Moreno et al., 2021). The WEF nexus approach seeks to understand the interconnections between WEF resources, optimise the synergies, minimise the trade-offs, and harmonise actions to enhance resource security for economically efficient, socially equitable and environmentally sustainable development (Mpandeli et al., 2018; Naidoo et al., 2021). The WEF nexus can serve three main roles—conceptual framework, discourse and analytic tool (Nhamo et al., 2020a)—and the latter dimension has witnessed the development of several WEF nexus tools with diverse characteristics and abilities (Taguta et al., 2022b). However, the majority of WEF nexus tools lack key attributes such as ready availability and accessibility, user-friendly platforms and graphical user interface (GUI), applicability at multiple scales, including local, compatibility with qualitative or mixed data, and geospatial analytic capabilities (Taguta et al., 2022b). This motivated the development of improved WEF nexus tools such as the geospatial web-based integrative analytical tool for the water-energy-food nexus (iWEF), some of whose key strengths include free availability and accessibility, a user-friendly GUI, scale versatility, compatibility with stakeholder-based qualitative data, and geospatial analytic capabilities (Taguta et al., 2023).

Southern Africa has witnessed significant WEF nexus work at multiple scales, including policy dialogues (GWP-SA, 2022), and the development of tools and their application in case studies (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Simpson et al., 2022; Taguta et al., 2023). However, despite the importance of hydrologic and sub-national boundaries in resource allocation and management, and service delivery, respectively (COGTA, 2020a; DWS, 2021; Sachs et al., 2023), only a minority of WEF nexus studies have focused on strategic scales such as water management areas (Nanfuka and Oosthuizen, 2023), catchments (Dlamini et al., 2023) and local municipalities (Nhamo et al., 2020b) in southern Africa. This undermines the application of the WEF nexus approach in transforming resource allocation, management, and service delivery.

This study, by assessing the state of the WEF nexus, examined evidence to inform the implementation of this approach for integrated management of WEF and related resources at sub-national scales to improve service delivery in southern Africa, specifically in South Africa and Zimbabwe. The research aimed to explore the state of the WEF nexus and to proffer interventions for improved integrated management of WEF resources at sub-national scales in

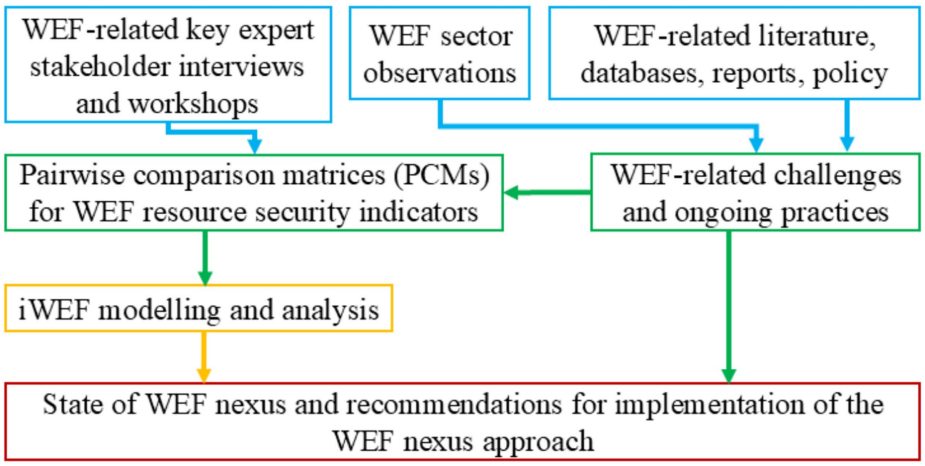


FIGURE 1
Study flowchart.

southern Africa, particularly at the water management area and catchment levels, using the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe) as case studies. It is hypothesised that the sustainability of integrated management of WEF resources is suboptimal in these case studies, with suboptimal WEF nexus indices and unbalanced management of WEF resources, and that there is a need for interventions to improve the status quo at sub-national scales. Thus, the research also aimed to identify priority areas for intervention, as well as ongoing and planned interventions, and their interconnections in the two selected case study areas in South Africa and Zimbabwe.

2 Materials and methods

Revealing and understanding the interconnections between WEF resources and sectors, as well as their integration, can be enhanced by a combination of, among others, modelling, technological innovations, and stakeholder participation (Beekma et al., 2021). Thus, this study employed mixed methods to assess the state of the WEF nexus in the Inkomati-Usuthu Water Management Area in South Africa and the Mzingwane Catchment in Zimbabwe. The nexus analytics approach specifically included integrated WEF nexus modelling with the iWEF tool (the geospatial web-based integrative water-energy-food nexus analytical modelling tool),[1] utilising inputs from expert key stakeholders (Taguta et al., 2023), complemented by assessments through observations, and data from databases and literature (Figure 1). In this way, modelling in the iWEF tool was based on stakeholder input, and the interpretation of its outcomes was supported by data and information from these sources.

2.1 Selection of case study areas

This study selected hydrologic boundaries as case studies, namely water management areas and catchments, because they are important units in WEF-related resource management and allocation for integrated, sustainable and equitable socioeconomic development in southern Africa (Ringler et al., 2018; DWS, 2023). A water management area in South Africa is a management unit within which a catchment management agency conducts the protection, use, development, conservation, management and control of water resources (GoSA, 1998). In Zimbabwe, a catchment area naturally drains into a dam, lake, reservoir, river or watercourse, and it supplies water to the water bodies through surface or ground flow originating from rainfall (GoZ, 1998). Inkomati-Usuthu Water Management Area is located in Mpumalanga province (South Africa), which is witnessing WEF-related interconnected challenges and developments, including energy generation, decommissioning of coal-fired power stations, irrigated agriculture and competition for land between sectors in an environment of water stress due to overallocation, groundwater depletion and climate change, among others (WRC, 2017; Simpson et al., 2019; IUCMA, 2023a). The Mzingwane Catchment in Zimbabwe is developing and implementing renewable energy projects, dam construction, irrigation expansion, and water transfers to address water scarcity, a growing population, and climate change and variability (ZimStat, 2023a; GoSA, 2024).

2.1.1 Inkomati-Usuthu Water Management Area (South Africa)

Inkomati-Usuthu Water Management Area in Mpumalanga Province is in the north-eastern part of South Africa and borders Mozambique and Eswatini, and is one of the nine water management areas (WMAs) in South Africa (Figure 2; DWS, 2016; IUCMA, 2022a).

The water management area is divided by the great escarpment (along the Graskop, Sabie, Nelspruit and Barberton axis) into the western plateau (Highveld) and the sub-tropical Lowveld in the east, and these changes in altitude in the two topographic areas give rise to spatial and temporal diversity in climate, especially rainfall, temperature and evapotranspiration (Table 1; IUCMA, 2019; EDM, 2021; IUCMA, 2022a; Mcinga, 2022).

The Lowveld region is hotter, has more fertile soils and is home to relatively poorer people (IUCMA, 2022a). Inkomati-Usuthu Water Management Area consists of four sub-catchments, namely

1 https://www.iwef.app/

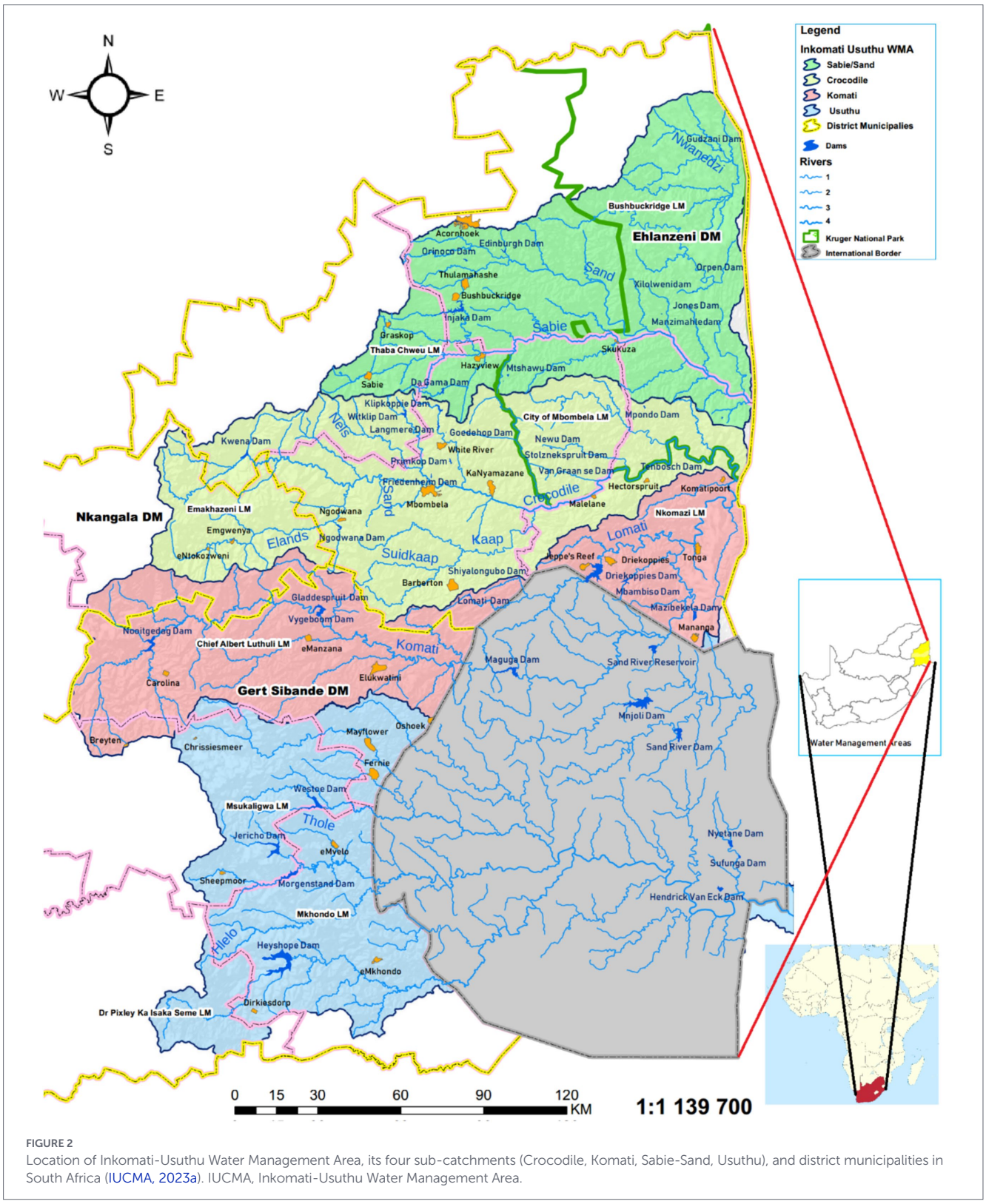


FIGURE 2
Location of Inkomati-Usuthu Water Management Area, its four sub-catchments (Crocodile, Komati, Sabie-Sand, Usuthu), and district municipalities in South Africa (IUCMA, 2023a). IUCMA, Inkomati-Usuthu Water Management Area.

Sabie-Sand (9,304 km^2), Crocodile (10,446 km^2), Komati (8,621 km^2), and Usuthu (7,785 km^2), all named after the respective four major rivers (DWS, 2016; IUCMA, 2022a). The water management area bounds the primary drainage region X and the portions of the tertiary drainage regions W51 to W56 falling within the boundary of South Africa (DWS, 2016). The major dams in Inkomati-Usuthu Water Management Area include Nooitgedacht, Vygeboom, Da Gama, Witklip, Kwena, Driekoppies, Heyshope, Inyaka, Jericho, Klipkoppies, Longmere, Morgenstond, Primkop and Westoe (IUCMA, 2023a). The water management area covers parts of three district municipalities, namely Ehlanzeni, Nkangala, and Gert Sibande, as well as nine local municipalities in these districts (Vester, 2019). The majority of the inhabitants reside in rural areas (StatsSA, 2022; StatsSA, 2023a). Socioeconomic challenges in the Inkomati-Usuthu Water

TABLE 1 Characteristics of Inkomati-Usuthu Water Management Area in South Africa and Mzingwane Catchment in Zimbabwe.

Characteristics	Case study	
	Inkomati-Usuthu Water Management Area (South Africa)	*Mzingwane Catchment (Zimbabwe)*
Approximate area (km^2)	36,256	63,000
Hosting river basins	Incomati and Maputo	Limpopo
Climate	Semi-arid and diverse. Sub-tropical climate. Hot summers and mild to cool winters.	Arid to semi-arid.
Rainfall	Seasonal rainfall (wet summers, dry winters), ranging from 400 mm/yr. (east) to 1,200 mm/yr. (west).	Irregular, erratic, and spatially and temporally variable and deficient. Decreases from north to south. 635 mm/yr.
Temperature	Mean annual temperature is 17 °C, average of maximum temperatures is 21 °C (January), average of minimum temperatures is 11.5°C (June) [excluding Usuthu sub-catchment].	Maximum temperature increases from north to south. Average daily maximum temperature: 22 °C to 34 °C. Average minimum temperature: 5 °C to 22 °C.
Evapotranspiration (mm/yr. per year)	1,800 (east) to 2,200 (west)	1,592
Total population (people)	2.5 million	874,000
Annual population growth rate (% per annum)	1.9 (Nkangala DM) through 2.0 (Gert Sibande DM) to 2.9 (Ehlanzeni DM)	1.0 (Masvingo) through 1.1 (Matabeleland South) to 1.2 (Midlands)
Average household size	3 to 4	4 to 5
Main economic activities	Agriculture (including irrigation), forestry, industry, electricity generation, mining, and eco-tourism.	Agriculture (including irrigation and livestock), mining, eco-tourism, and industry.

Sources: (i) IUWMA, Inkomati-Usuthu Water Management Area (InhlakaniphoConsultants, 2008; Jovanovic et al., 2015; IUCMA, 2019; IUCMA, 2020; DWS, 2021; EDM, 2021; Mallory and Magagula, 2021; Deventer et al., 2022; IUCMA, 2022a; Mcinga, 2022; StatsSA, 2022; IUCMA, 2023a; IUCMA, 2023b; Nanfuka and Oosthuizen, 2023; StatsSA, 2023a; StatsSA, 2023b); (ii) MC, Mzingwane Catchment (LBPTC, 2010; Love et al., 2010; UNEP, 2010; LIMCOM, 2011; Zhu and Ringler, 2012; LIMCOM et al., 2017; Manatsa et al., 2020; Sibanda et al., 2020b; Maviza et al., 2022; ZimStat, 2023b; ZimStat, 2023a); DM, district municipality.

Management Area and its constituent sub-catchments, districts and local municipalities include poverty and inequality (StatsSA, 2019; Vester, 2019). For example, the Gini index for South Africa and Mpumalanga province is 0.63 and 0.60, respectively, due to highly imbalanced income distributions, which consequently cause disparities between social groups in access to strategic resources such as water and sanitation, productive land, and supporting infrastructure for effective farming practice (MPG, 2015; COGTA, 2020b).

2.1.2 Mzingwane Catchment (Zimbabwe)

Mzingwane Catchment is in the northern parts of the Limpopo River Basin and the south-western parts of Zimbabwe, and is located between 19.8° and 22.4° S and 27.7° and 32.0° E (Figure 3; Table 1; LBPTC, 2010; Sibanda et al., 2020; Maviza et al., 2022).

Mzingwane Catchment is one of the seven catchments in Zimbabwe, and it consists of four sub-catchments, namely Shashe (20,140 km^2), Upper Mzingwane (2,138 km^2), Lower Mzingwane (26,936 km^2), and Mwenezi (13,786 km^2; LBPTC, 2010; Sibanda et al., 2020; Maviza et al., 2022; Figure 3). The catchment has five major rivers (Shashe, Umzingwane, Mwenezi, Bubi and Marico) that feed into the Limpopo River (Figure 3; LIMCOM et al., 2017; Sibanda et al., 2020). The catchment straddles parts of three provinces (Matabeleland South, Masvingo and Midlands), nine rural districts (Beitbridge Rural, Gwanda Rural, Mangwe, Umzingwane, Matobo, Insiza, Chiredzi Rural, Mwenezi, Mberengwa), three urban districts (Beitbridge Urban, Gwanda Urban, Plumtree), and 197 wards (Figure 3; ZimStat, 2023b). Mzingwane Catchment is home to around 214,645 households (ZimStat, 2023b) and the total population is projected to reach 889,293 and 904,924 people by 2030 and 2040, respectively (LIMCOM et al., 2017). The population density per square kilometre in Mzingwane Catchment ranges from 14 (Matabeleland South), through 29 (Masvingo), to 37 (Midlands; ZimStat, 2023b), while approximately 85% of the catchment's population lives in rural areas (Mabiza et al., 2007; LIMCOM et al., 2017). Beitbridge is the economic hub and a major urban and industrial centre in the catchment, serving as the main gateway for trade between South Africa and Southern and East Africa. High poverty in the catchment is driven by limited livelihood options available to most of the population and the unfavourable climate, which complicates the main livelihood source for most households, i.e., agriculture (GoZ, 2022f).

Mzingwane Catchment is situated mainly in revised agro-ecological zones (AEZs) IV, Va and Vb, with a small portion in AEZ III. These zones are characterised by low annual rainfall and poor soil quality. Thus the Catchment is mainly suitable for semi-intensive and extensive livestock production (beef, dairy, goats, poultry, wildlife), irrigated agriculture (maize, soybean, groundnuts, cotton, sunflower, watermelons, sugarcane, tree plantations [oranges, lemons, lime]), and rainfed production of drought tolerant crops (sorghum, finger millet, pearl millet, cowpeas; Manatsa et al., 2020). The catchment experiences warm temperatures, a dry winter season and a hot, wet summer season (October to March), whose highest rainfall occurs between December and February (Love et al., 2010), most of which is lost to high rates of evapotranspiration (UNEP, 2010; LIMCOM, 2011; Sibanda et al., 2020). National water resources management interests and priorities in the Mzingwane Catchment are mainly irrigation expansion to at least 4,000 hectares (from the existing 3,000 ha and a potential of 10,900 ha) by 2025, irrigation rehabilitation and modernisation, agricultural development, and expanding water storage (LIMCOM et al., 2017; Dickens et al., 2020; ZimVAC and FNC, 2022d;

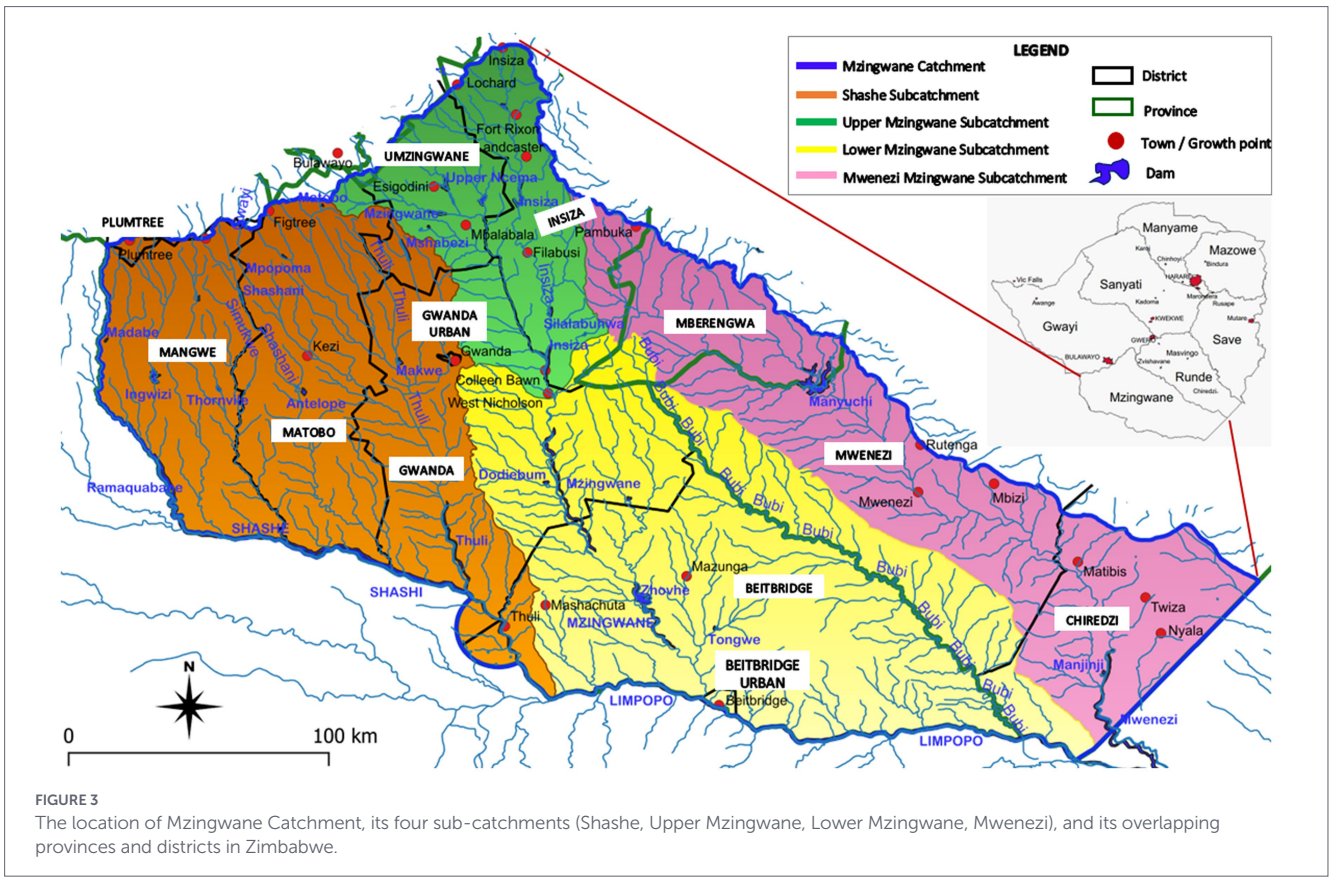


FIGURE 3
The location of Mzingwane Catchment, its four sub-catchments (Shashe, Upper Mzingwane, Lower Mzingwane, Mwenezi), and its overlapping provinces and districts in Zimbabwe.

ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). Similarly, the Government of Zimbabwe signed a Memorandum of Understanding with the Government of South Africa on 14 March 2024, under which the former will sell 15 Mm^3 of treated water monthly to the latter by 2026. The water will originate from Zhovhe Dam in the Mzingwane Catchment, be treated at Beitbridge Water Treatment Works, and then be transferred across the border to Musina Town (GoSA, 2024). Considering the World Health Organisation (WHO) recommended benchmark of basic water requirement of 50 litres per person per day, the planned water sale of 41 ML/day would be sufficient to supply 820,000 people (164000–205,000 households) per day with domestic water from an improved source, for drinking, food preparation, bathing and general sanitation (Gondo and Kolawole, 2022). Instead of selling this water to South Africa, it could go a long way in bridging existing gaps in safe water supply in urban and rural areas surrounding Beitbridge (ZimStat, 2023a). Thus, water remains and will likely continue to be a major limitation to development in the Mzingwane Catchment (LIMCOM, 2011).

2.2 The geospatial web-based integrative water-energy-food nexus analytical modelling tool (iWEF 1.0)

For analysing the sustainability of management of WEF resources from an integrated nexus perspective in the case study areas, this study applied the geospatial web-based integrative water-energy-food nexus analytical modelling (iWEF) tool (Taguta et al., 2023). The iWEF model was initially developed as a WEF nexus analytical livelihoods framework (ALF; Mabhaudhi et al., 2019) and a spreadsheet-based integrative analytical model for the water-energy-food nexus (Nhamo et al., 2020a), which was further enhanced into an open-access geospatial web-based integrative water-energy-food nexus analytical modelling tool (Taguta et al., 2023). In its previous versions, iWEF was successfully applied at a regional scale (southern Africa; Mabhaudhi et al., 2019), national scale (South Africa; Nhamo et al., 2020a) and local scale (Sakhisizwe Local Municipality, South Africa; Nhamo et al., 2020b). Key strengths of the current version of the iWEF tool include free availability and accessibility, a user-friendly GUI, scale versatility, compatibility with stakeholder-based qualitative data, and geospatial analytic capabilities (Taguta et al., 2023).

The current version of the iWEF model (December 2025) integrates a Geographic Information Systems (GIS) module that facilitates the geospatial location of case studies and spatial analysis of the WEF nexus (Taguta et al., 2023). The iWEF model supports integrated assessment of WEF resource management using the Analytic Hierarchy Process (AHP) multi-criteria decision-making (MCDM; Appendix A; Saaty, 1987; Saaty and Vargas, 2012a). To establish quantitative relationships among WEF nexus sustainability indicators, the sustainability indicators in the iWEF model are based on the pillars of sustainability (i.e., availability, accessibility, productivity, affordability, stability, safety, reliability, type, sufficiency) and measure the security of WEF resources (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Taguta et al., 2023). The six indicators in the iWEF tool (Table 2), calculated for the analysis period, such as per annum, are by no means a comprehensive set of indicators of WEF resource security, but are adequately indicative.

TABLE 2 The six indicators in the iWEF model (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b; Taguta et al., 2023).

Sector	Indicator	Definition	Units
Water	Water availability	Proportion of available freshwater resources per capita	m^3/capita
	Water productivity	Economic output or benefit per unit of water consumed	$/$m^3$
Energy	Energy accessibility	Proportion of the total population with access to electricity	%
	Energy productivity	Economic output or benefit derived from each unit of energy used	$/MJ
Food	Food self-sufficiency	Proportion of the total population who have sufficient food during the reference year	%
	Cereal (or crop) productivity	Proportion of sustainable agricultural production per unit area	kg/ha

While the naming of the six indicators in the current version of the iWEF tool was adopted from Mabhaudhi et al. (2019) and Nhamo et al. (2020a), the polarity and definitions of energy productivity and food self-sufficiency were reversed to align with the rest of the indicators (Taguta et al., 2023), so that higher indicator values are desirable for resource security. To quantitatively assess the state of the WEF nexus in the iWEF tool, the six indicators are compared or ranked on their relative pairwise performance or importance against each other in a pairwise comparison matrix (PCM) by stakeholders (expert or non-expert or both) based on the Saaty AHP and scale (Appendix B), and sometimes supported by, if available, quantitative values of the six indicators based on expert opinion, literature, or recognised databases (e.g., national statistics, World Bank, Aquastat; Mabhaudhi et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b; Taguta et al., 2023). The Saaty AHP scale ranges from 1 (equal importance) to 9 (the highest and most significant relationship; Appendix B; Saaty, 1977; Saaty, 1987). Thus, the key inputs in the iWEF model are (i) stakeholders' pairwise comparison matrices (PCMs) developed from their pairwise judgements of the six iWEF indicators, and (ii) boundary delineations for the case study areas (Taguta et al., 2023). Delineations of the case study boundaries in the iWEF model can be performed manually in the "Map Playground" or automatically by uploading pre-existing shapefiles in .geojson format (Taguta et al., 2023).

The computation module of iWEF performs three key tasks: (i) determining the consistency (logical accuracy) of the input PCM of the WEF security indicators, (ii) calculating and normalising indices of WEF security indicators by the AHP-MCDM technique, and (iii) calculating the integrated WEF nexus composite index (Appendix A; Taguta et al., 2023). Key outputs from the iWEF model include the (i) consistency ratio (CR) whose value is indicative of the consistency of the stakeholder judgements in PCMs, (ii) integrated WEF nexus composite index indicative of the overall WEF nexus performance of the case study, (iii) spider diagram or radar chart or sustainability polygon plotted on a common scale from the normalised indices which indicates the relative performance of each indicator and sector from an integrated nexus perspective, and (iv) map which shows the geographic location and WEF nexus performance of the case study. The value of the integrated WEF nexus composite index ranges from 0.048 (low) to 0.286 (high; Taguta et al., 2023). Due to its linear computation method (Appendix A), the integrated WEF nexus composite index assumes compensability across normalised indices of indicators, i.e., a deficit in one normalised indices can thus be offset (compensated) by a surplus in another since they all add up to one (1; OECD, EU and EC-JRC, 2008). Thus, in the interpretation of findings from the AHP-based iWEF tool, compensability is necessary for highlighting interconnections, i.e., trade-offs and synergies, across the six WEF indicators that have different units. More information on the iWEF model, including the scaled categories of performance of the six WEF-related indicators and the integrated WEF nexus composite index, is available in (Appendix A) and the background papers (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b; Taguta et al., 2023).

2.3 Selection and engagement of WEF-related expert key stakeholders

WEF nexus studies engage diverse stakeholders in various ways, depending on the context, including objectives and spatial scale. WEF nexus studies at local scale such as household tend to engage relatively higher numbers of stakeholders, up to hundreds of individuals or households (Casazza et al., 2021), while those at medium to large scales relevant for policy and decision-making levels have engaged relatively low numbers of stakeholders ranging from two (2; Tan and Yap, 2019) to tens of key informants (Johnson and Karlberg, 2017; Sušnik et al., 2021). Regarding sampling methods, the latter category of studies usually uses non-probability sampling techniques, including those based on expertise, purposive, convenient, systematic, stratified, and quota- or proportion-based (White et al., 2017; Adom et al., 2022; Chemura et al., 2025). Stakeholder engagement in WEF nexus studies utilises various interactive methods, including interviews, workshops, focus group discussions, and surveys (González-Rosell et al., 2020). Regarding purposive sampling, it is recommended to engage 3–30 participants in qualitative research, depending on the proposed analysis, the level of detail required, and the emphasis on homogeneity versus heterogeneity (Palinkas et al., 2015). Thus, this study used expertise-based, purposive and snowball sampling to identify 20 WEF-related expert key stakeholders in the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe). This sampling strategy was perceived as useful for identifying and selecting a diverse and nearly sectorally balanced set of key stakeholders knowledgeable of and responsible for the management of WEF-related resources in the two selected water management areas and catchment case study areas (Martinez et al., 2018; González-Rosell et al., 2020; Eriksson et al., 2025). In Inkomati-Usuthu Water Management Area, the selected 20 stakeholders were primarily involved in water (8), energy (6), food and agriculture (7) and environment and climate (3) sectors in key organisations such as Eskom, Inkomati-Usuthu Catchment Management Agency (IUCMA), Catchment Management Forums (CMFs), and strategic provincial, district, and local government

departments. These stakeholders in the Inkomati-Usuthu Water Management Area were engaged through interviews, meetings, workshops, and surveys, the latter conducted during catchment management forum meetings for the sub-catchments, including Crocodile, Komati, and Usuthu, in October to November 2022. On the other hand, the selected 20 stakeholders in Mzingwane Catchment work primarily in water (9), energy (5), food and agriculture (7) and environment and climate (3) sectors in relevant organisations including Zimbabwe National Water Authority (ZINWA), Zimbabwe Electricity Supply Authority (ZESA), Environmental Management Agency (EMA), and strategic provincial, and district government departments. These stakeholders in Mzingwane Catchment were engaged through interviews, meetings and surveys in November to December 2022.

2.4 Data collection

2.4.1 Indicator pairwise judgements as qualitative WEF nexus data

A survey instrument was used to elicit the opinions and perceptions of WEF-related expert key stakeholders (planners, managers, decision-makers, and policymakers) regarding the status of managing WEF resources in the two selected case study areas: the Inkomati-Usuthu Water Management Area and the Mzingwane Catchment. The key stakeholders were experts from WEF-related sectors, including water, energy, electricity, agriculture, food, irrigation, environment, and climate. For the pairwise comparison rankings of WEF sustainability indicators, expert key stakeholders from WEF-related sectors were asked, based on their perception and knowledge of the case study, to qualitatively and quantitatively pairwise compare the performance of the six indicators using Saaty's AHP scale (Appendix B).

For each case study, the judgements from individual expert key stakeholders were systematically aggregated by multiplying the averages of each set of reciprocals and rounding up or down the outcome depending on their proximity to the Saaty scale values (1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 1, 2, 3, 4, 5, 6, 7, 8, 9). This mixed method combines and complements the components and strengths of both the aggregation of individual judgments (AIJ) and the aggregation of individual priorities (AIP) in AHP settings (Forman and Peniwati, 1998). The expert key stakeholders' resulting aggregated PCMs (i.e., judgements) were initially run in the iWEF model to check their consistency. The real-world judgements of people faced with multiple criteria (e.g., the six WEF security indicators) are subjective, rarely perfectly consistent, and sometimes fairly inconsistent (Forman and Selly, 2001). If a stakeholder states that "water availability" performs better than "water productivity" and "water productivity" performs better than "energy productivity," their judgments become highly random and inconsistent if they mention that "energy productivity" performs better than "water availability." If judgments have a consistency ratio of $CR \geq 0.1$, it is the normal procedure in the AHP method to review data for the criteria, e.g., indicator(s), that is/are out of the desired interval (Benítez et al., 2012; Salomon and Gomes, 2024).

Techniques for improving the consistency of judgements in AHP include optimisation by, among others, manual methods that are computationally demanding, or the use of simple automated tools (Benítez et al., 2012). The latter techniques facilitate the exploration of inconsistencies in the matrix by locating and improving the most inconsistent judgement(s). These tools include Expert Choice AHP Software[2] and AHP Priority Calculator[3] (Goepel, 2022), among others. The AHP Priority Calculator (Goepel, 2022) was used in this study to assess and improve consistency due to its ready availability, free and open access, and optimisation technique based on mathematics that captures the interconnections between pairwise comparisons (Salomon and Gomes, 2024). Where and when the PCMs from stakeholders showed inconsistency (consistency ratio, $CR \geq 0.1$) in the iWEF model (Mu and Pereyra-Rojas, 2017), the PCMs were run in the AHP Priority Calculator (Goepel, 2022) which systematically (i) checked for consistency, (ii) identified the specific pairwise judgements that are inconsistent, and (iii) advised on ranges of consistent values for the outlier judgements. If unacceptable, these initial consistency results were presented to the participating stakeholders to guide them in iteratively reconsidering and revising their pairwise judgements with a particular focus on the outlier judgements. In this way, the stakeholders reviewed their judgments and validated the improvements in comparison (Salomon and Gomes, 2024). A very low inconsistency (e.g., 0) is necessary but not sufficient for a good decision in AHP. Thus, in this study, the standard AHP consistency threshold ($CR < 0.1$) was adopted, as the AHP does not require perfect consistency (Forman and Selly, 2001).

For the Inkomati-Usuthu Water Management Area in South Africa, the shapefiles for delineating the case study boundaries in the iWEF tool were obtained from the Municipal Demarcation Board and the Department of Water and Sanitation (DWS) Spatial Data Download Tool. Similarly, the shapefiles for delineating the boundaries of the Mzingwane Catchment (Zimbabwe) were obtained from the Zimbabwe National Water Authority (ZINWA) and DabaneTrust (ZINWA and DabaneTrust, 2022) and the Humanitarian Data Exchange by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA).

2.4.2 Quantitative WEF nexus data

The quantitative data for WEF nexus security indicators to support interpretation of the results from iWEF modelling for the two case studies were obtained or derived from relevant established databases, archives and publications including those from statistical agencies (Statistics South Africa [Stats SA], Zimbabwe National Statistics Agency [ZimStat]), government publications (reports, policies, strategies, census, surveys), and literature. Thus, various sources and existing open data were leveraged to synthesise and enhance knowledge of the WEF nexus from otherwise isolated domains (Sowby and Dicataldo, 2022). Data from government sources, such as Stats SA (for the Inkomati-Usuthu Water Management Area) and ZimStat (for the Mzingwane Catchment), is demarcated along administrative boundaries, not hydrological boundaries. Out of the six indicators (Table 2), those that were not available in databases and reports were estimated, based on available data, using the definitions and relationships in Table 2 (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b; Taguta et al., 2023). Wherein the hydrological boundary, such as water management area or catchment, does not fully align with administrative boundaries, variables such as population were estimated by proportionally distributing the published

2 https://www.expertchoice.com/

3 https://bpmsg.com/ahp/ahp-calc.php

TABLE 3 Final PCMs for rankings of WEF resource security indicators (judgements) by WEF-related expert key stakeholders and the normalised indices for Inkomati-Usuthu Water Management Area (CR = 8.3%) and Mzingwane Catchment (CR = 8.6%).

Indicator	WA		WP		EA		EP		FSS		CP	
	IUWMA	*MC*	*IUWMA*	*MC*	*IUWMA*	*MC*	*IUWMA*	*MC*	*IUWMA*	*MC*	*IUWMA*	*MC*
WA	1	1	1.00	1.00	0.20	0.50	1/3	2.00	0.20	1/3	0.20	1.00
WP	1.00	1.00	1	1	1/3	0.50	1/2	2.00	1/3	0.50	1/3	1.00
EA	5.00	2.00	3.00	2.00	1	1	1.00	2.00	1.00	2.00	3.00	2.00
EP	3.00	0.50	2.00	0.50	1.00	0.50	1	1	1.00	2.00	1/3	1.00
FSS	5.00	3.00	3.00	2.00	1.00	0.50	1.00	0.50	1	1	1/3	2.00
CP	5.00	1.00	3.00	1.00	1/3	0.50	3.00	1.00	3.00	0.50	1	1
Normalised index	0.05	0.13	0.07	0.14	0.27	0.26	0.15	0.14	0.18	0.21	0.28	0.12

CR, consistency ratio; WA, water availability; WP, water productivity; EA, energy accessibility; EP, energy productivity; FSS, food self-sufficiency; CP, crop productivity; IUWMA, Inkomati-Usuthu Water Management Area (South Africa); MC, Catchment (Zimbabwe).
Shaded cells represent pairwise comparison of an indicator against itself.

value for a spatial unit (province, district or local municipality) over the part of the unit that falls in the hydrological boundary (Aurecon, 2013).

3 Results

3.1 The state of the WEF nexus in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe)

The initial PCMs for Inkomati-Usuthu Water Management Area in South Africa were inconsistent (consistency ratio, $CR > 0.1$), with consistency ratio (CR) values of 14.1%. A revision of the inconsistent PCMs by stakeholders resulted in final consistent PCMs (Table 3) with an acceptable consistency ratio (CR) for Inkomati-Usuthu Water Management Area (8.3%; Figure 4).

The initial pairwise comparison matrices (PCMs) of WEF-related indicators from expert key stakeholders for the Mzingwane Catchment were inconsistent with CR values of 15.6% (Mu and Pereyra-Rojas, 2017). The same stakeholders were re-engaged iteratively to systematically revise some of their outlier judgements, yielding final, consistent PCMs (Table 3) with acceptable consistency ratios (CR) for the Mzingwane Catchment (8.6%; Figure 4).

The quantitative values of the six indicators of the security of WEF sectors for Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe) confirm the suboptimal security and sustainability of management of WEF resources in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe), although with mixed performances for individual indicators across and even within individual case studies (Table 4).

Considering the security and sustainability of managing WEF resources in Inkomati-Usuthu Water Management Area (South Africa), the situation is unsustainable for water availability and water productivity, marginally sustainable for energy productivity and food self-sufficiency, moderately sustainable for energy accessibility, and highly sustainable for cereal (or crop) productivity (Table 4). The performance of individual indicators in the Mzingwane Catchment ranges from unsustainable for water availability, water productivity, energy productivity, and cereal (or crop) productivity, through marginally sustainable for energy accessibility, to moderately sustainable for food self-sufficiency (Table 4).

3.1.1 The state of the WEF nexus in Inkomati-Usuthu Water Management Area (South Africa)

With an iWEF-generated integrated WEF nexus composite index of 0.209 (from a maximum of 0.286; Taguta et al., 2023) based on stakeholder-based PCMs of the relative performance of six indicators in the Inkomati-Usuthu Water Management Area, it is evident that the management of WEF resources is moderately sustainable from an integrated nexus perspective, that is, suboptimal (Figure 4). The irregular shape of the centrepiece in the spider diagram is evidence of unbalanced management of the WEF resources in the water management area (Figure 4). For example, the energy and food sectors (pillars) and their indicators perform relatively well compared to the water sector (pillar) and its indicators (Figure 4). Cereal productivity and energy accessibility are faring better than all other indicators, followed by food self-sufficiency, energy productivity, and water productivity and water availability (Figure 4). These trends in performance can be attributed to various challenges and resource management practices prevalent in the water management area, as reported by expert key stakeholders in the water management area and in the literature related to the WEF resources and sectors.

3.1.1.1 Water security in Inkomati-Usuthu Water Management Area

Approximately 80% of households in Inkomati-Usuthu Water Management Area have access to safe drinking water, and 29.1% of the population reported safe and reliable water supply as the biggest challenge, while the cost or affordability of water was ranked the fifth highest challenge (6.4%) faced in their municipalities (StatsSA, 2018; MPG, 2022b; StatsSA, 2023a; StatsSA, 2023c). Meanwhile, the estimated reliability of water supply and sanitation services in the water management area is 63% (DWS, 2018a). The low performance in water availability is attributed to water scarcity (Table 4), deficit-driven and stress-driven by population growth and urbanisation (e.g., Mbombela, White River), limited water resources, and poor water

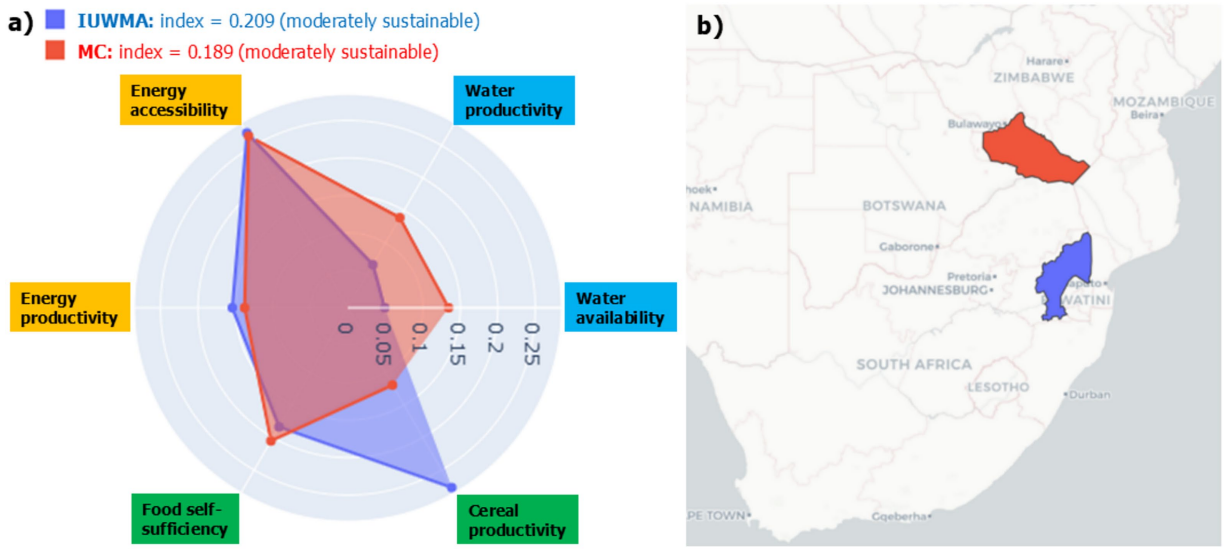


FIGURE 4
For Inkomati-Usuthu Water Management Area (IUWMA, South Africa) and Mzingwane Catchment (MC, Zimbabwe): **(a)** Quantitative and graphical representation of the normalised indices (unitless) for the six WEF-related indicators in iWEF; and **(b)** spatial visualisation of the WEF nexus (Colour codes in the map are only for distinction and identification of case studies; all normalised indices of the six indicators use the same scale in the spider diagram/radar chart/sustainability polygon. Data source: Key WEF-related expert stakeholders and the iWEF model).

TABLE 4 Overview of the WEF nexus indicators for Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe).

Nexus dimension	Indicator and units	Case study		Scaled categories of performance for WEF-related indicators[14]			
		IUWMA (South Africa)	MC (Zimbabwe)	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
Water	Water availability (WA, m^3/cap/yr)	886.8[1,2]	1021[3,4,5]	$WA < 1700$	$1700 \leq WA \leq 6{,}000$	$6{,}000 < WA \leq 15{,}000$	$WA > 15{,}000$
	Water productivity (WP, $/m3)	4.11[1,2]	2.00[3,4,5,6,7]	$WP < 10$	$10 \leq WP \leq 20$	$20 < WP \leq 100$	$WP > 100$
Energy	Energy accessibility (EA, %)	87.2[8,9,10]	21.5[4,5,7,11]	$EA < 20$	$20 \leq EA \leq 50$	$50 < EA < 90$	$90 \leq EA \leq 100$
	Energy productivity (EP, $GDP/MJ)	0.12[8,9,10]	0.09[4,5,6,7,11]	$EP < 0.11$	$0.11 \leq EP < 0.2$	$0.2 \leq EP \leq 0.33$	$EP > 0.33$
Food	Food self-sufficiency (FSS, %)	83.9[9]	87.9[12,13]	$FSS < 70$	$70 \leq FSS \leq 85$	$85 < FSS \leq 95$	$FSS > 95$
	Cereal (or crop) productivity (CP, kg/ha)	5418.4[9]	302.5[7,12,13]	$CP < 500$	$500 < CP \leq 2000$	$2000 < CP \leq 4{,}000$	$CP > 4{,}000$

IUWMA, Inkomati-Usuthu Water Management Area; MC, Mzingwane Catchment.
Sources: Department of Water and Sanitation—DWS (1); Inkomati-Usuthu Catchment Management Agency—IUCMA (2); Zimbabwe National Water Authority—ZINWA (3); Limpopo Basin Permanent Technical Committee—LBPTC (4); Limpopo Watercourse Commission—LIMCOM (5); Government of Zimbabwe (6); Zimbabwe National Statistics Agency—ZimStat (7); Eskom (8); Statistics South Africa—Stats SA (9); Government of South Africa (10); Zimbabwe Power Company—ZPC, Zimbabwe Electricity Supply Authority—ZESA and Zimbabwe Energy Regulatory Authority—ZERA (11); Food and Nutrition Council—FNC and Zimbabwe Vulnerability Assessment Committee—ZimVAC (12); Department of Agricultural Technical and Extension Services—AGRITEX (13); (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Taguta et al., 2023) (14).

management. Other challenges include poor water quality, climate conditions, disparities in access to water, limited water storage infrastructure, and continued and sometimes uncontrolled (unregulated) expansion of economic activities (agricultural, mining, industrial; IUCMA, 2020; EDM, 2021; Roselt and Mabila, 2022).

The ratio of water deficit to supply in Inkomati-Usuthu Water Management Area ranges from 29 to 37%, with values of 0.2% (Usuthu) to 14.8% (Crocodile), considering the ecological reserve (Mallory and Magagula, 2021; Roselt and Mabila, 2022). Similarly, the rate of groundwater recession over the years within the water management area has been higher than the rate of replenishment, and groundwater remains relatively available in all sub-catchments except for Sabie-Sand (IUCMA, 2022a; IUCMA, 2023a; IUCMA, 2023b). However, efforts to access groundwater are hampered by a lack of adequate water infrastructure (MPG, 2020). Water security in the water management area is compromised by climate change and

climate variability, including rainfall, evapotranspiration and extreme events (EDM, 2021; IUCMA, 2022a; Roselt and Mabila, 2022). Historical climate data for 1960–2021 shows a spatially coherent reduction in precipitation (March–April–May), the 90th percentile rainfall and rain days (DEA, 2013b; IUCMA, 2021; IUCMA, 2022a; IUCMA, 2023a), and an increased annual mean and 90th percentile maximum and minimum temperatures are evident in the Inkomati-Usuthu Water Management Area (DEA, 2013b). The El Niño-induced drought in 2015/16 severely affected water availability in the water management area, and its residual effects persisted until the 2019–2020 hydrological year, during which low water availability impacted water use sectors such as agriculture and power generation (DEA, 2013b; IUCMA, 2019). Projections for climate change in Inkomati-Usuthu Water Management Area point to a drier and warmer future climate with higher temperatures (minimum, average and maximum), increased drought incidences and evapotranspiration, which will continue to affect the security of water resources and related sectors adversely (DEA, 2013b; Shai, 2021; Mcinga, 2022).

The catchment's population continues to grow (Table 1), thus exerting pressure on demand for the available water resources (StatsSA, 2023a; StatsSA, 2023c), and is further complicated by the high urbanisation, influx of migrants and the mushrooming of mining communities and informal settlements (Balzer, 2020; Mpandeli et al., 2020; Roselt and Mabila, 2022; StatsSA, 2023c). Migration continues to increase and ranks as the third most influential component of demographic change (StatsSA, 2023b). Meanwhile, Mpumalanga province hosts over 7% of the country's migrant population (the 5th-highest among nine provinces; StatsSA, 2018; Mukumbang et al., 2020). Other challenges to water security in the Inkomati-Usuthu Water Management Area include alien vegetation, which currently consumes approximately 3% of available water resources (IUCMA, 2023a), drying up of dams, insufficient bulk water storage infrastructure, and illegal connections and water abstraction (IUCMA, 2020; MPG, 2022b; Roselt and Mabila, 2022). Water quality in the water management area is compromised by insufficient and dysfunctional water and wastewater treatment works, and contamination and pollution of water (surface, groundwater) by industrial effluent and sewage, poor municipal waste management practices, mining activities, and soil erosion from agricultural activities (EDM, 2021; Roselt and Mpofu, 2021; Shai, 2021; IUCMA, 2022a).

The low water productivity in the Inkomati-Usuthu Water Management Area is due to suboptimal water-use efficiencies across water distribution and various use sectors, including domestic, energy generation, and irrigated agriculture. For example, non-revenue water, distribution water losses (municipal, domestic), and irrigation water losses in the water management area are high at 36–46.2%, 12–30% and 30–40%, respectively (Vester, 2019). Producing and sending out 1 kWh of electricity in Inkomati-Usuthu Water Management Area consumes an average of about 1.4 ℓ of water across all technologies, which is on the higher side of the world average of 1.2–1.5 ℓ/kWhSO (litres per kilowatt-hour sent out; Pocock and Joubert, 2021; Roselt and Mpofu, 2021; WRC, 2021). Although Eskom used to achieve its target specific water consumption for electricity production in the past, this trend was reversed and exacerbated from around 2016 to date due to the prevalence of water-intensive wet recirculation-cooled coal-fired stations in the Eskom power stations fleet, decreasing thermal efficiency, low load factors, poor water management practices (leaks, overflows) and increasing age profile of the power plants (Figure 5a; Pocock and Joubert, 2021; WRC, 2021; Eskom, 2024a; Eskom, 2024b).

As a result, energy generation, specifically in coal-powered stations, has remained a major and strategic water user in the Inkomati-Usuthu Water Management Area (Figure 5b; Eskom, 2024a; Eskom, 2024b). Poor irrigation scheduling and water-inefficient irrigation systems in smallholder farms undermine irrigation efficiency and water productivity in the water management area (Shai, 2021). Water productivity is also impacted by domestic water use and consumption, which is higher than the national and international benchmark and world average (173 ℓ/c/d; DWS, 2021; Roselt and Mpofu, 2021).

3.1.1.2 Energy security in Inkomati-Usuthu Water Management Area

The moderately sustainable performance in energy indicators is due to some households still using non-modern energy sources for cooking, lighting and heating. For example, about 82.8, 88.8, 83.8 and 63.3% of households in Mpumalanga Province use electricity for cooking, lighting, water heating and space heating, respectively, while the rest use gas, solar and unclean sources of energy such as paraffin, fuel generators, firewood, coal, animal dung, and candles (StatsSA, 2016; StatsSA, 2025). Most households in the Inkomati-Usuthu Water Management Area that use polluting energy sources are not connected to the national electricity grid, and the adoption of clean cooking technologies, such as biogas, is limited (Shai, 2021). Approximately 6.7% of the population cited the cost and affordability of electricity as one of the top five challenges in the region (StatsSA, 2018), while the reliability of the electricity supply is severely undermined by loadshedding and electricity interruptions (Figure 6; StatsSA, 2025).

For example, South Africa stayed in a National State of Disaster (Impact of Severe Electricity Supply Constraint) for 2 months in 2023, that is, from February to April (GoSA, 2023b; GoSA, 2023c; GoSA, 2023a). In 2023, South Africa experienced approximately 6,947 h of load shedding, comprising a total of 335 days compared to fewer days in the previous years, that is, 205 days in 2022, 75 days in 2021, 54 days in 2020, 30 days in 2019, 14 days in 2018, and none in 2017 and 2016 (Figure 6; TheOutlier and EskomSePush, 2023). Low energy productivity in the Inkomati-Usuthu Water Management Area can be attributed to relatively high and persistently increasing electric power transmission and distribution losses at 11.9% in South Africa (Eskom, 2024a) compared to the global average of 6% of total output (Figure 6; WorldBank, 2025). Energy experts in Inkomati-Usuthu Water Management Area cited other challenges of maintenance delays, shortage of materials (steel, copper cables, solar panels, containers, lithium batteries, converters), theft and vandalism of key infrastructure (copper cables, transformers, transformer oil), the ongoing closure of some base load coal-fired power generation plants (e.g., Komati), illegal electricity connections (izinyoka), and inefficient use of energy at domestic/household level through use of inefficient and energy-intensive appliances.

3.1.1.3 Food security in Inkomati-Usuthu Water Management Area

High cereal productivity in Inkomati-Usuthu Water Management Area can be attributed to good maize yields (5.81 tons/ha; Table 4) and a relatively high number of households (18.2%) involved in agricultural activities, including crop production (grain, food; StatsSA, 2016; StatsSA, 2020). The relatively high maize yields

can be attributed, among other factors, to the widespread use of irrigation (StatsSA, 2020) and the application of fertiliser (82% synthetic, 12% organic, 1% others) on around 95% of commercial farms in Mpumalanga (Shai, 2021). Marginally sustainable food self-sufficiency was characterised by the prevalence of running out of money to buy food and skipping a meal in the last 12 months, at 23 and 15%, respectively (StatsSA, 2018). Although households are involved in agriculture on small pieces of land to produce food for their households and generate some income (StatsSA, 2016), the proportion of agricultural households has decreased by 14.5% since 2011 (StatsSA, 2016; Mcinga, 2022). Other causes for concern for food security in Inkomati-Usuthu Water Management Area include rapid urbanisation, the changes in diets and the growing middle class, increasing food losses and waste along the agri-food chain, low adoption of conservation agriculture practices (≤30% of grain sector), degraded soils, limited use of organic fertilisers (12% of commercial farms), climate change, and limited land tenure rights. Soil degradation is due to poor farming practices (overgrazing, invasive plants, land clearing, uncontrolled veld fires) and mining activities, the latter of which claims about 14% of high-potential arable land, while 40% is subject to prospecting activities (MDEDT, 2011; Shai, 2021; Mcinga, 2022). Mining activities also exacerbate competition for arable agricultural land (Simpson et al., 2019; Mcinga, 2022).

Inconsistent and incoherent land reform policies and water use allocations undermine agricultural productivity, especially among smallholder irrigated farmers (DWS, 2018a; DWS, 2018b; Mcinga, 2022). Climate conditions are affecting food security in the Inkomati-Usuthu Water Management Area, and future climate changes are likely to exacerbate hunger and malnutrition. Maize yield variabilities in the water management area are significantly positively correlated with agrometeorological variables (Simanjuntak

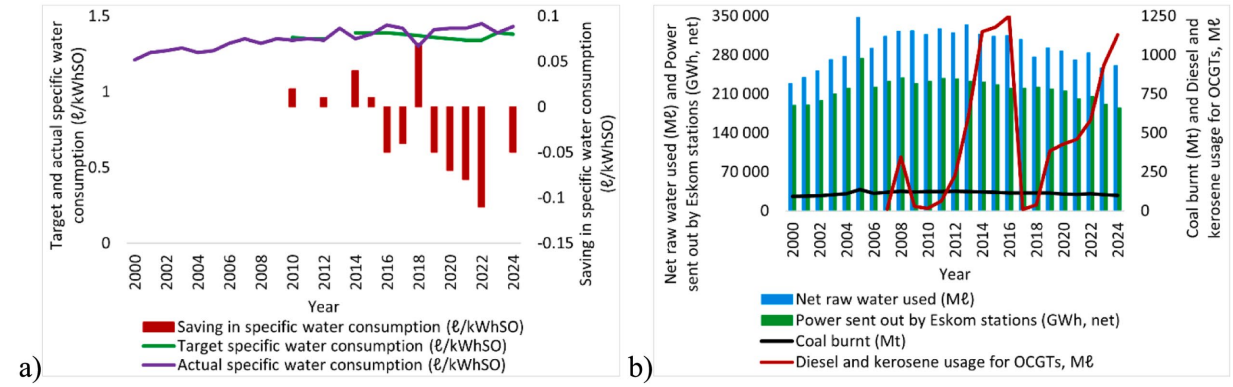


FIGURE 5
For the period 2000–2024, Eskom's **(a)** specific water consumption (l/kWhSO), **(b)** inputs (raw water [Ml], coal [Mt], and liquid fuel (diesel and kerosene) [Ml]; Eskom, 2024a; Eskom, 2024b).

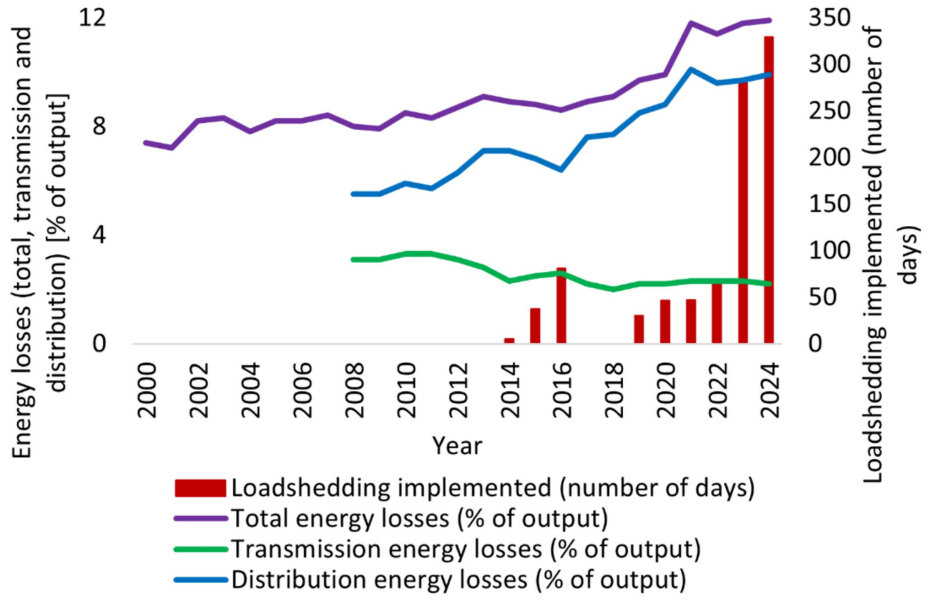


FIGURE 6
Eskom's total electric power losses (total, transmission, and distribution) [%] and occurrence of loadshedding (number of days) for the period 2000–2024 (Eskom, 2024a).

et al., 2022). Current climate variability significantly affects food production, while climate change will likely undermine future agricultural productivity through decreasing yields of major crops such as maize, soya beans, dry beans, and sunflower by approximately 19–65%, 11–38%, 16–42%, and 5–30%, respectively (DEA, 2013a; Olabanji et al., 2021).

3.1.2 The state of the WEF nexus in Mzingwane Catchment (Zimbabwe)

With an iWEF-generated integrated WEF nexus composite index of 0.189 (from a maximum of 0.286; Taguta et al., 2023) calculated from stakeholder-based pairwise comparison matrices (PCMs) of the relative performance of six WEF-related indicators, it is evident that the management of WEF resources is moderately sustainable from an integrated nexus perspective, that is, suboptimal in the Mzingwane Catchment (Figure 4). The irregular shape of the centrepiece in the spider diagram is evidence of unbalanced management of the WEF resources in the catchment (Figure 4). At the sector level, the energy sector outperforms the food sector, followed by the water sector (Figure 4). At the indicator level, energy accessibility and food self-sufficiency are faring well, followed by energy productivity, water productivity, water availability, and cereal productivity (Figure 4). Several challenges to WEF security were reported by expert key stakeholders in the literature and observed in the case study areas (Figure 7).

3.1.2.1 Water security in Mzingwane Catchment

Approximately 75% of households in Mzingwane Catchment have access to improved sources of water for drinking, while the rest access water from unprotected water sources for household requirements, which has resulted in the spread of water-borne diseases (ZimStat, 2023a). With a total storage in water reservoirs of 1,210 Mm^3 (Murwira and Yachan, 2007; LIMCOM et al., 2017), the catchment supplies 60 Mm^3/annum of water to Bulawayo City, which is located on the watershed of the Umzingwane and Gwayi catchments (Mkandla et al., 2005; LIMCOM et al., 2017). Mzingwane Catchment is water-stressed and is challenged with water scarcity, as evidenced by dried-up river beds and dams (Figures 7a–c), and per capita water availability of below 1700 m^3/year (Table 4), which will likely fall to chronic levels of below 1,000 m^3/capita per year in 2030 (Falkenmark et al., 1989; Alemaw et al., 2008; Dickens et al., 2020). This is due to the decommissioning of large dams (LIMCOM et al., 2017; UN-Habitat and TongjiUniversity, 2022), lack of repair and maintenance (Mufute et al., 2008), land degradation (Figures 7d,e) and siltation (Figures 7f,g) driven by multiple practices and challenges in the catchment (LIMCOM, 2011; LIMCOM et al., 2017; GoZ, 2022f). For example, 48% of water sources are compromised by siltation (35.1%), breached or broken dam walls (6.2%) and leaking (GoZ, 2022b; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h). Poor land management practices and illegal mining cause water pollution by chemicals such as mercury and cyanide, which are harmful to human health (Dalu et al., 2017;

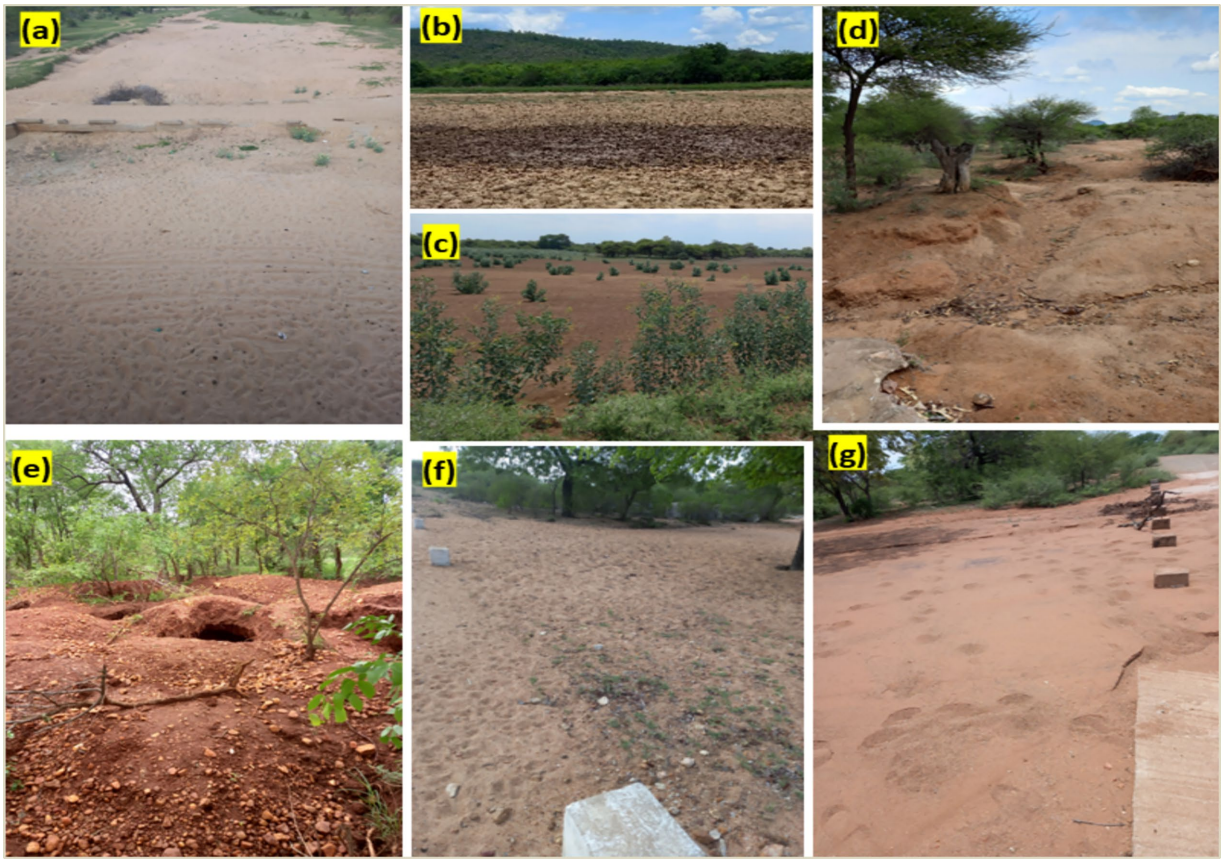


FIGURE 7
From Mzingwane Catchment; dry **(a)** river beds at Pendi, and dams in **(b)** Esibomvu, and **(c)** Mashaba; **(d)** land degradation at Mashaba; **(e)** artisanal mining in Gwanda; and siltation in **(f)** Tuli and **(g)** Mashaba (photos were taken by the author during the last week of November 2022, i.e., during the wet season which typically starts in late October and ends in March; Sibanda et al., 2020).

Makwerere et al., 2018; Mambrey et al., 2020; Masere and Sibanda, 2024). The situation is exacerbated by the inadequacy of water treatment chemicals and equipment (e.g., pumps) due to high costs and the unavailability of foreign currency (Remigios and Never, 2010; Musemwa, 2021; Brooke and Fenner, 2023).

Mzingwane Catchment generally has deep water tables and low-productivity groundwater resources (LIMCOM, 2011) and about 19% of boreholes in Mzingwane Catchment are not supplying water due to drying, water table shifts, collapsed rods or pipes, lack of maintenance and funds, shortage of spare parts, vandalism, incorrect siting, pipes not reaching the water table, and droughts (GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j). Apart from surface (flow and stored) and groundwater (boreholes, wells), the sand river beds in alluvial aquifers are a valuable source of fresh water resources in the catchment, especially for domestic use, irrigation and livestock watering, particularly among rural communities along main rivers, including Limpopo, Thuli, Umzingwane, Mwenezi and Shashe (Alemaw et al., 2008; Duker et al., 2020; Kapangaziwiri et al., 2021). Water productivity is undermined by the dominance of water-inefficient flood irrigation, which accounts for more than half of the total irrigated area in the Mzingwane Catchment (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022e; GoZ, 2022j; GoZ, 2022k). According to some key stakeholders, including experts from ZINWA and the irrigation sector, as well as water users such as farmers, some individuals use water illegally by irrigating without permits and deliberately extracting more water than their allocated amount.

3.1.2.2 Energy security in Mzingwane Catchment

In the energy sector, connection to the electricity grid (national and mini) is generally low (22%) in the Mzingwane Catchment, and the situation is worse in rural areas (19%) than in urban areas (47%; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC and FNC, 2022c; ZimStat, 2023a). The unconnected rural and urban households tend to use polluting fuels for cooking, lighting and heating, including firewood (78%), coal, charcoal, animal dung, paraffin lamps, grass/straws, candles and oil lamps (Dickens et al., 2020; ZimStat, 2023a). However, disparities exist between urban (40%) and rural households (90%) in the use of firewood for cooking (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e; ZimVAC and FNC, 2022a). The use of polluting fuels causes indoor air pollution, which contribute to ill health and deaths (WHO, n.d.), while the cutting down of trees for firewood is a major cause of deforestation and land degradation in Zimbabwe (Moyo, 2019; Mubaiwa, 2021). Despite their relatively high connectivity to electricity networks, urban people suffer from frequent and prolonged electricity load shedding, which dates as far back as the 2000s (GoZ, 2012a). Meanwhile, household adoption of renewable energy and efficient electric appliances is low and slow, while inefficient water use in irrigated agriculture undermines energy productivity in the Mzingwane Catchment.

3.1.2.3 Food security in Mzingwane Catchment

Cereal productivity performed relatively poorly despite the (i) increase in area under small-scale irrigation during the period 2013 to 2018, (ii) stable cereal prices, (iii) introduction of input support scheme through "command agriculture," and (iv) increase in the area under climate-proofed technologies and initiatives (Pfumvudza / Intwasa). Despite these promising interventions and conditions, maize production in the Mzingwane Catchment was still suboptimal due to poor rainfall and longer dry spells (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; AU, 2023; FSIN and GNAFC, 2023), and the average maize yield remained lower than the 3,600 kg/ha for the Limpopo River Basin (LIMCOM et al., 2017). Food security is undermined by the operational status of irrigation schemes in Mzingwane Catchment, wherein the majority of the irrigated area (approximately 68%) is either partly functional or not functional (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022k; GoZ, 2022e). Partly- and non-functional irrigation schemes are undermined by challenges related to inadequate infrastructure, insufficient resources, poor operation, management and governance and maintenance, wildlife-human conflicts, unfavourable land tenure system, economy, markets and prices, old age of the plot holders, pests and disease outbreaks, and climate (Dickens et al., 2020; GoZ, 2022b; GoZ, 2022d; GoZ, 2022h; GoZ, 2022e; GoZ, 2022j; GoZ, 2022k; ZimVAC and FNC, 2022d). In the food, agriculture, and water sectors, inflation, local currency instability, and funding constraints hinder the resuscitation of irrigation schemes and water sources, including boreholes. A majority of irrigation schemes in the Mzingwane Catchment depend on dams and rivers (84.1% by area). Dams and rivers (84.1% by area) and grid electricity (52%) are the main sources of water and energy, respectively, and this exposes agriculture and food security to the risks of intermittent supplies of water and electricity (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022e; GoZ, 2022j; GoZ, 2022k).

The relatively good performance of food self-sufficiency (87.9%) under low cereal productivity can be attributed to relaxation of import bans and duties on basic commodities, including food, and assistance from government and development partners, including grain, porridge and pulse meals (WorldBank, 2019; Muhoyi and Mbonigaba, 2022; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b). Some households received remittances from the diaspora and urban areas in the form of mobile transfers of cash and food, the former of which is also used to buy food, among others (Ndlovu et al., 2020; Sithole et al., 2023; Moyo, 2024). Coping strategies by poor rural households during lean times include the consumption and sale of wild fruits and insects, as well as exchanging casual labour for cereals (GoZ, 2022f; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). The COVID-19 restrictions undermined food security (GoZ, 2022i). Miners invade agricultural land, and this has caused some conflicts with farmers, while the former leave open pits wherein livestock fall and die (LIMCOM, 2011; GoZ, 2022b; GoZ, 2022f). Other challenges include livestock theft and the unavailability of the labour force in agriculture, as youth embark into mining or migrate to neighbouring countries in search of economic opportunities. There is a general prevalence of poor agricultural practices (e.g., streambank cultivation) and the absence of soil and water conservation measures, such as contours (GoZ, 2022f).

3.1.3 Summarising the state of the WEF nexus in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe)

Findings from this mixed-method study show that the sustainability of integrated management of WEF resources is suboptimal and unbalanced in the Inkomati-Usuthu Water Management Area and Mzingwane Catchment (Figure 4; Table 4). Table 5 provides a

TABLE 5 Summarising the state of the WEF nexus in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe).

Resource sector	Sectoral dimension	Case study	
		IUWMA (South Africa)	MC (Zimbabwe)
Integrated WEF	Integrated WEF nexus composite index	• Moderately sustainable	
	State of integrated management of resources	• Unbalanced	
Water	Availability	• Unsustainable • Access to safe drinking water • Reliability of water supply • Cost or affordability of water • Water scarcity, deficit and stress • Water quality • Water infrastructure • Groundwater depletion • Alien vegetation • Illegal connections and water abstraction	• Unsustainable • Access to safe drinking water • Water scarcity and stress • Water infrastructure • Inflation and local currency instability
	Productivity	• Unsustainable • Water use efficiencies in water distribution and various use sectors • Non-revenue water • Distribution water losses (municipal, domestic), • Irrigation water losses and inefficiency • Specific water consumption for electricity production. • Domestic water use and consumption per capita per day	• Unsustainable • Water-inefficient flood irrigation • Illegal use of water for irrigation • Water theft
Energy	Accessibility	• Moderately sustainable • Access to modern energy sources for cooking, lighting and heating • Cost and affordability of electricity • Reliability of the electricity supply, e.g., loadshedding and electricity interruptions • Theft and vandalism of key energy infrastructure • Closure of some base load coal-fired power generation plants	• Marginally sustainable • Access to the electricity grid • Reliability of the electricity supply, e.g., loadshedding • Adoption of renewable energy
	Productivity	• Marginally sustainable • Electric transmission power losses • Electric distribution power losses • Illegal electricity connections • Use of inefficient and energy-intensive appliances	• Unsustainable • Adoption of efficient electric appliances
Food	Self-sufficiency	• Marginally sustainable • Involvement of households in agricultural activities • Running out of money to buy food • Skipping a meal in the last 12 months • Food losses and waste	• Moderately sustainable • Stable cereal prices • Low cereal productivity • Relaxation of import bans and duties on basic commodities • Food assistance from government and development partners • Remittances and mobile transfers of cash and food • Consumption and sale of wild fruits and insects • Exchanging casual labour for cereals • COVID-19 restrictions

(Continued)

TABLE 5 (Continued)

Resource sector	Sectoral dimension	Case study	
		IUWMA (South Africa)	MC (Zimbabwe)
	Productivity	• Highly sustainable • Use of irrigation in agriculture • Use of fertiliser in agriculture • Adoption of conservation agriculture practices • Land tenure rights • Agricultural practices • Competition for arable land • Inconsistent and incoherent land reform policies and water use allocations • Land degradation	• Unsustainable • Expansion of small-scale irrigation • Agricultural input support scheme • Expansion of area under climate-proofed agriculture • Small-scale irrigation infrastructure and management • Land tenure • Pests and disease outbreaks • Reliance of irrigation on dams, rivers and grid electricity for water and energy • Competition for arable land • Labour force in agriculture • Agricultural practices • Land degradation
Crosscutting		• Population growth • Urbanisation and uncontrolled (unregulated) expansion of economic activities (agricultural, mining, industrial) • Climate variability and change	

IUWMA, Inkomati-Usuthu Water Management Area (South Africa); MC, Mzingwane Catchment (Zimbabwe).

summary of the state of the WEF nexus in the two case study areas and these can serve as diagnostic baselines for policymakers, planners, decisionmakers and practitioners.

3.2 The location effect on the WEF nexus: Inkomati-Usuthu Water Management Area and Mzingwane Catchment

Although the purpose of this study was not to compare but to assess the state of the WEF nexus at the sub-national planning and water allocation scales in the two countries in southern Africa, i.e., catchment and water management area, some differences were noted in findings from iWEF modelling and quantitative values of the six indicators, from place to place (Section 3.1). The Inkomati-Usuthu Water Management Area and the Mzingwane Catchment are both hydrologic boundaries, but the former has a higher integrated WEF nexus composite index (0.209) than the latter (0.189; Figure 4). Similarly, the relative performance of the six WEF security indicators differs, as evidenced by the different normalised indices in the two hydrologic case studies (Figure 4). In the Inkomati-Usuthu Water Management Area, the highest- and lowest-performing indicators from an integrated nexus perspective are cereal productivity and water availability, respectively. In contrast, in the Mzingwane Catchment, the highest- and lowest-performing indicators are energy accessibility and cereal productivity, respectively (Figure 4). Considering the quantitative values of the six WEF indicators, the only similarity between the Inkomati-Usuthu Water Management Area and the Mzingwane Catchment is the categorisation of water availability and water productivity as unsustainable. At the same time, the former case study area has one indicator performing as highly sustainable, i.e., cereal (or crop) productivity, and the latter case study has none in this high category (Table 4). These differences in the WEF nexus across locations and spatial scales may be due to the diversity of characteristic conditions, including demography (e.g., population size and distribution), socioeconomic conditions, meteorology (climate and weather), infrastructure (e.g., resource production and distribution networks), management practices and governance, and the economic structure, which determines the nature of WEF systems. Such factors and drivers determine the nature and magnitude of interconnections in WEF systems, as well as the supply, demand, and management of resources. Thus, WEF dynamics vary spatially, temporally, and across scales/levels, and require localised analysis to inform the development and implementation of context-specific interventions. This calls for improved nexus tools that can spatially analyse and disaggregate WEF dynamics and interconnections (Taguta et al., 2022b).

4 Discussion

4.1 State of the WEF nexus in South Africa, Zimbabwe and southern Africa

The findings from this study align with those from previous studies, particularly regarding the suboptimal sustainability of WEF resources across various scales from a nexus perspective in South Africa. It was reported that the management of WEF resources from a nexus perspective is not sustainable at multiple scales, including regional (SADC; Mabhaudhi et al., 2019), national (Nhamo et al., 2020a; South Africa), and municipal (Sakhisizwe Local Municipality, South Africa; Nhamo et al., 2020b). This is evidenced by the stiff competition for land and water between coal mining for energy generation and food production in Mpumalanga province (Simpson et al., 2019), water insecurity and precarious WEF interconnections at the household level in Melani and Hamburg communities (Eastern Cape Province; Ningi et al., 2021), and the trade-offs in the lateral inflation between food, energy and water at the national level (Ngarava, 2021). Projections point to a bleak future through the perpetuation of the "business as usual" management of WEF resources in South Africa, which will likely undermine the reliability of water systems in Cape Town (Ding et al., 2021) and the Buffalo River catchment (Dlamini et al., 2023).

In Zimbabwe, communities in the Harare City region are connected to national resource grids but rely on groundwater, firewood, charcoal, gas, mobile tuckshops, and backyard and open-space farming as sources of WEF resources (Gandidzanwa and Togo, 2022). Rural households in Chivi District (Masvingo Province) are facing WEF insecurities. Some of their coping strategies are not sustainable (Jaka et al., 2023), while Bulawayo City is famous for its water restrictions and rationing, which date back to 1938 and 1949, respectively (Mkandla et al., 2005; Chirisa and Bandauko, 2015). Gomo et al. (2018) found that tree cover declined by 4.6%, while cropland increased by 16%, and urban areas doubled in size between 1992 and 2015 in the Zambezi River Basin (ZRB). Future WEF resources demand, competition, interconnections, and interdependencies are expected to intensify in Zimbabwe. Zimbabwe is a riparian country of ZRB, where (Koundouri and Papadaki, 2020) found that WEF resource demands are expected to double during the period 2018 to 2060 due to only demographic development, while a combination of economic development and international trade will put an additional burden on the supply chain to meet those goals. These previous studies in southern Africa also highlight that the WEF nexus varies with location, spatial scale and temporal scale, even when using the same WEF nexus tool and in the same region (Mabhaudhi et al., 2019; Koundouri and Papadaki, 2020; Nhamo et al., 2020a; Nhamo et al., 2020b; Mabhaudhi et al., 2021; Dlamini et al., 2023).

4.2 Entry points for improving WEF resource security in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe)

Assessment of the nexus using modelling based on stakeholder qualitative inputs, as well as observation and quantitative data from the literature, indicates suboptimal management and security of WEF resources in the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe). The findings (Figure 4; Table 4) provide diagnostic baselines that policymakers, planners, decision-makers, and practitioners can use to identify context-specific priority entry points for intervening to improve the management of WEF resources towards their sustainability and security.

The priority sector for intervention in both case study areas is water, as evidenced by the low relative performance of water indicators, namely water availability and water productivity (Figure 4; Table 4). The following priority sectors are energy and food in the Inkomati-Usuthu Water Management Area, and the opposite is true in the Mzingwane Catchment (Figure 4; Table 4). At the indicator level, the descending order of prioritisation in the Inkomati-Usuthu Water Management Area should be to improve (i) water productivity and water availability, followed by (ii) food self-sufficiency and energy productivity, and then (iii) energy accessibility and cereal productivity (Figure 4; Table 4). In the Mzingwane Catchment, the descending order of prioritisation for improvement should be (i) cereal productivity, water availability, water productivity, and energy productivity, followed by (ii) food self-sufficiency and energy accessibility (Figure 4; Table 4). This mixed composition of WEF sectoral indicators, in the order and levels of prioritisation for improvement, across both case study areas, emphasises the need for integrated approaches, such as the nexus, to manage cross-sectoral synergies and trade-offs.

4.3 Improving the status of the WEF security from an integrated nexus perspective in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe)

4.3.1 WEF resource management and governance in South Africa and Zimbabwe

The Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe) face challenges related to WEF security (ZimStat, 2023a; StatsSA, 2025) and achieving sustainable development (AU, AfDB, UNDP and UNECA, 2025; Sachs et al., 2025). The management of WEF resources is not sustainable from an integrated nexus perspective, and there is a gap and a need for improvement (Sections 3.1–3.2). Evidence, such as that in Figure 4 and Table 4, informs us about entry points for intervention, for example, indicators and pillars/sectors with low normalised indices and low quantitative indicator values. Several efforts are being made to improve WEF security in the two case study areas, for example, in the Mzingwane Catchment (Figure 8).

However, it is highly likely that these and other initiatives were planned and are being implemented from a sectoral and silo perspective, which will potentially exacerbate trade-offs and competition, and the challenge is to find combinations of measures that have a net positive outcome (de Waal et al., 2019; Beekma et al., 2021; Lah, 2025). SADC, Zimbabwe, South Africa, and Inkomati-Usuthu Catchment Management Agency (IUCMA) echo that silo approaches are undermining programme cost-effectiveness and responsible for the decline in infrastructure, the slow pace in renewable energy development, and suboptimal implementation of programmes (SADC, 2016; IUCMA, 2019; GoZ, 2020b; Nepfumbada, 2020; DWS, 2022b). Managing such trade-offs and competition requires integrated and transformative approaches; South Africa and Zimbabwe can build on those they have already adopted, such as Integrated Water Resources Management (IWRM; GoZ, 2012b; DWS, 2021). Zimbabwe also applies the Whole of Government Approach (WoGA), which is based on integration (vertical and horizontal), joint programming, inclusivity, collective action, multilevel coordination, and engagement of stakeholders (e.g., development partners), for pooling resources together in implementing agriculture programs and projects (GoZ, 2020b; AU, 2023). Besides IWRM, South Africa embraced other integrated mechanisms for governing WEF-related resources, sectors and service delivery, including integrated resources planning (DMRE, 2023), the District Development Model (DDM; COGTA, 2020a; EDM, 2021) and the WEF nexus (DAFF, 2015; Nepfumbada, 2020; DWS, 2021), the latter of which has been embraced at the SADC regional level (Kabeya et al., 2022; SADC, 2023).

4.3.2 An integrated nexus perspective of ongoing and planned WEF-related practices and initiatives in Inkomati-Usuthu Water Management Area (South Africa) and Mzingwane Catchment (Zimbabwe)

Applying the integrated nexus approach to ongoing and planned WEF-related practices and initiatives potentially enhances understanding of interconnections between WEF resources (Figure 9), creates and strengthens synergies, minimises trade-offs, and harmonises actions to enhance resource security for balanced, economically

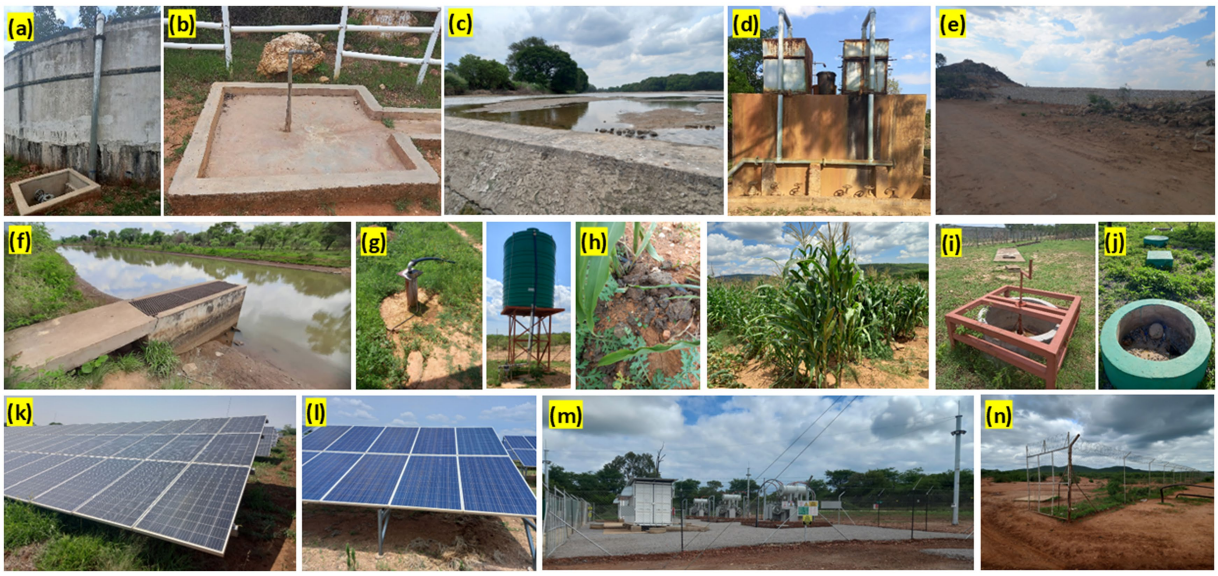


FIGURE 8
From Mzingwane Catchment: **(a)** ongoing expansion of Esigodini water treatment and supply system; **(b)** a private sector-funded community water supply scheme; **(c)** a sand dam at Tuli; **(d)** a sand dam water treatment and supply system at Ntepe; **(e)** ongoing construction of the Tuli-Moswa multi-purpose dam; **(f)** a dam supplying water at Mzinyathini irrigation scheme; **(g,h)** a solar-powered, drip-irrigated and organic manure fertilised community food and nutrition garden at Esibomvu; biogas digesters **(i)** supplying fuel for cooking and treated manure at a livestock farm and **(j)** energising at Gwanda Agricultural Show; and solar power plants **(k)** in construction at Richaw site in Gwanda, **(l)** energising the Mashaba community, **(m)** energising Blanket (Caledonia) Mine, and **(n)** in construction at a site in Gwanda.

efficient, socially equitable and environmentally sustainable development (Mpandeli et al., 2018; Naidoo et al., 2021).

Having identified the WEF interconnections (Figure 9), the next step is to quantify their polarities, intensities, and magnitudes using an integrated approach that includes modelling and simulation (Jain et al., 2023). Such evidence informs the creation and strengthening of synergies and co-benefits, as well as the management and minimisation of trade-offs, for example, through the development of packages of complementary interventions (Howe et al., 2014). For example, Mujere and Chanza (2022) employed a WEF nexus approach to examine the synergies and trade-offs associated with the Tugwi-Mukosi Dam (Zimbabwe), including social, economic, political, industrial, and environmental impacts on society. They provided recommendations for minimising the negative impacts.

4.3.3 Integrating solutions through the nexus approach

Solar water-heating (geysers) reduces grid energy demand and environmental pollution from emissions (Wlokas, 2011; Thobejane et al., 2019). Farmers are recommended to practice agroecology through cultivating crops and rearing livestock species that are suitable for their agroecological zones (Manatsa et al., 2020; GoZ, 2022k). Dams under planning and construction in Inkomati-Usuthu Water Management Area (e.g., Boschjeskop Dam [Nels River], Mountain View Dam [78 Mm^3/annum, Kaap River], and Strathmore Dam) and Mzingwane Catchment (Tuli-Manyange [33 Mm^3], Tuli-Mhosva [420 Mm^3], Glass Block / Bopoma Dam [126 Mm^3]) need to consider multipurpose systems that integrate water storage and supply, energy generation (hydropower, floatovoltaics), and food supply, including irrigated agriculture, agrivoltaics and aquaculture for increased resource productivity (ZINWA and DabaneTrust, 2022; IUCMA, 2023a). Additional water for irrigation in the Mzingwane Catchment can be obtained from alluvial aquifers along the major rivers, including the Shashe River, the Thuli River, the Mzingwane River, the Bubi area, the Mwenezi River, and the Mushawe River (Alemaw et al., 2008; Kapangaziwiri et al., 2021).

4.3.4 Unravelling and managing trade-offs through the nexus approach

Interventions such as groundwater exploitation for augmenting water supply, irrigation expansion for agricultural intensification and irrigation modernisation from 'low-efficient' surface methods to 'high-efficient' drip and sprinkler methods require additional energy for pumping, and this is bound to increase greenhouse gases (Taguta et al., 2022a). Plans for commercial hydrogen production in South Africa need to account for water and energy requirements and plan accordingly (IEA, 2023; Weidner et al., 2023). While it will leave the Mzingwane Catchment short of 15 Mm^3 (41 ML/day; GoSA, 2024), the planned water transfer scheme from Zhovhe Dam (Zimbabwe) to Musina town (South Africa) will also come at a cost to energy security, given the current state of loadshedding. Such energy-intensive interventions can harness and leverage the abundant renewable energy potential in the case study areas, including solar (ESMAP, 2020).

4.3.5 Centralising people in a nexus-based just transition

Central to the nexus approach are three founding guiding principles, including "accelerating access, integrating the poorest", which

seeks to put people at the centre of a just transition informed by the nexus approach (Hoff, 2011). van Huyssteen et al. (2023) found that shifting from fossil fuels (particularly coal) to non-hydro and non-biomass renewables will reduce the impact of electricity production on the water-energy-food-carbon emissions nexus sectors in South Africa. However, accelerating access while integrating the poorest is a key founding principle of the nexus approach (Hoff, 2011). An integrated, broadened and people-centred nexus approach can inform a just energy transition (JET) that seeks to balance competing interests between people (e.g., livelihoods, employment, human health), prosperity (e.g., energy security, economic growth) and the planet (e.g., greenhouse gas emissions, air quality, resource depletion, land degradation; NPC, 2019; Li and Zhang, 2023). Such an approach would prevent the perpetuation of pre-existing sets of winners and losers (Carley and Konisky, 2020), ensuring that the transition to a low-emissions economy is just, equitable, and inclusive, leaving no one behind (Li and Zhang, 2023). Given that the majority of people in the case studies reside in rural areas, this also calls for equal consideration of decentralised interventions for off-grid communities, such as those in remote, peri-urban, and rural areas. For example, biogas is a clean and environmentally friendly fuel whose use can potentially reduce deforestation, biodiversity loss, pollution-related illnesses and deaths, drudgery for women and girls in collecting fuelwood, land degradation, and emissions from waste and combustion (Kabeyi and Olanrewaju, 2022). Thus, decentralised and off-grid WEF solutions can promote the protection and conservation of natural capital and narrow the rural–urban divide (UNDESA, 2021).

4.3.6 Creating more with less

Central to the nexus approach are three founding guiding principles, including creating more with less, which seeks to improve resource use efficiency and productivity (Hoff, 2011). By achieving the set target specific water consumption of 1.38 ℓ/kWhSO instead of the actual specific water consumption of 1.43 ℓ/kWhSO in 2024 (Eskom, 2024a; Eskom, 2024b), Eskom (South Africa) would have saved about 0.05 ℓ/kWhSO, which translates to 10,242 Mℓ of water sufficient to support 142,249 indigent households with basic water for a whole year at six kilolitres per household per month (Ding et al., 2021). These water savings would also be accompanied by significant reductions in electricity generation costs. As such, to realise such synergies in the future, Eskom needs to make a stronger effort to achieve the target water consumption of 1.37, 1.36 and 1.36 ℓ/kWhSO in 2025, 2026 and 2027, respectively (Eskom, 2023; Eskom, 2024a). Similarly, by achieving the world average electric power losses (transmission and distribution) of 6% (WorldBank, 2025) instead of 11.9% of total electric power sent out by Eskom stations

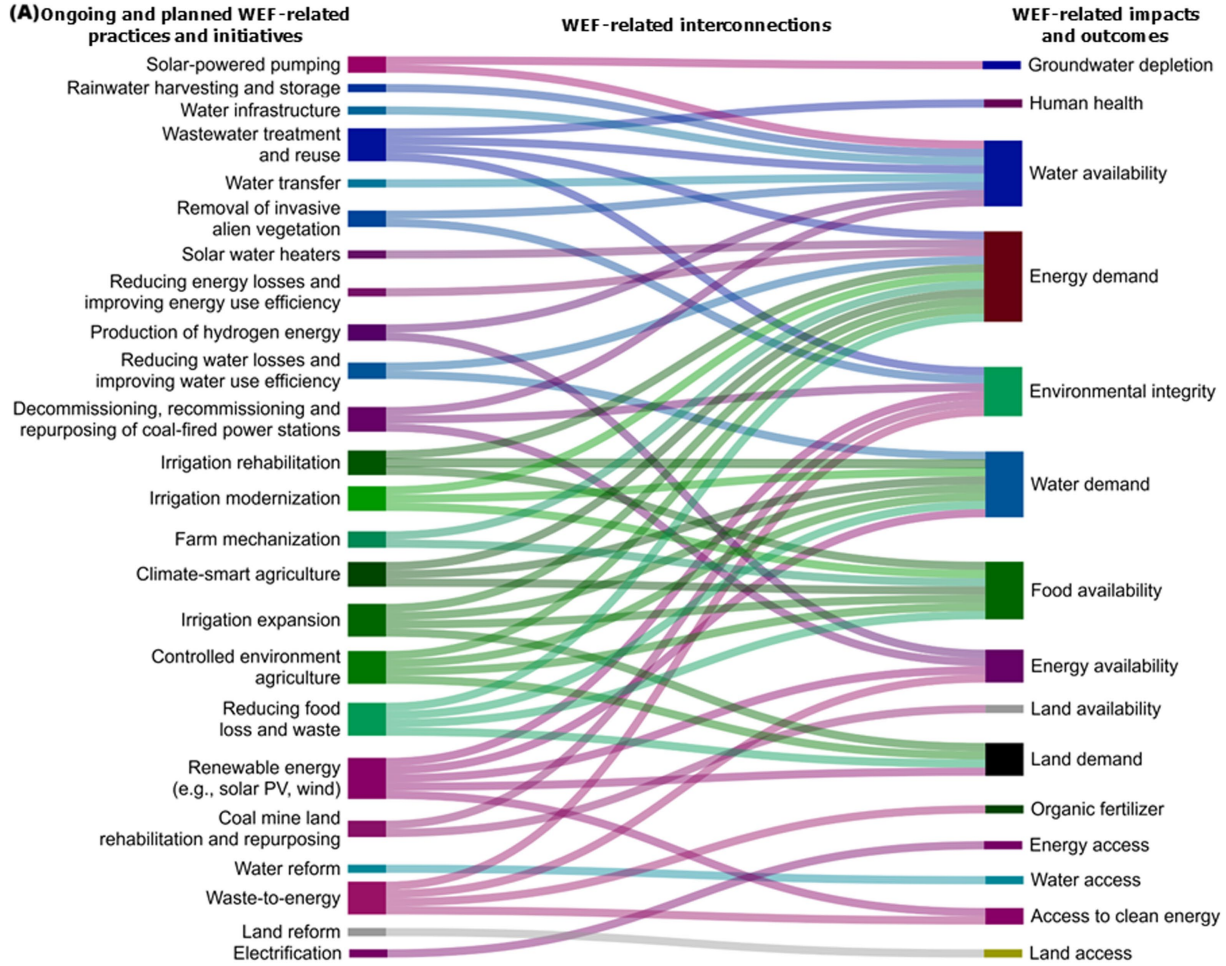


FIGURE 9 (Continued)

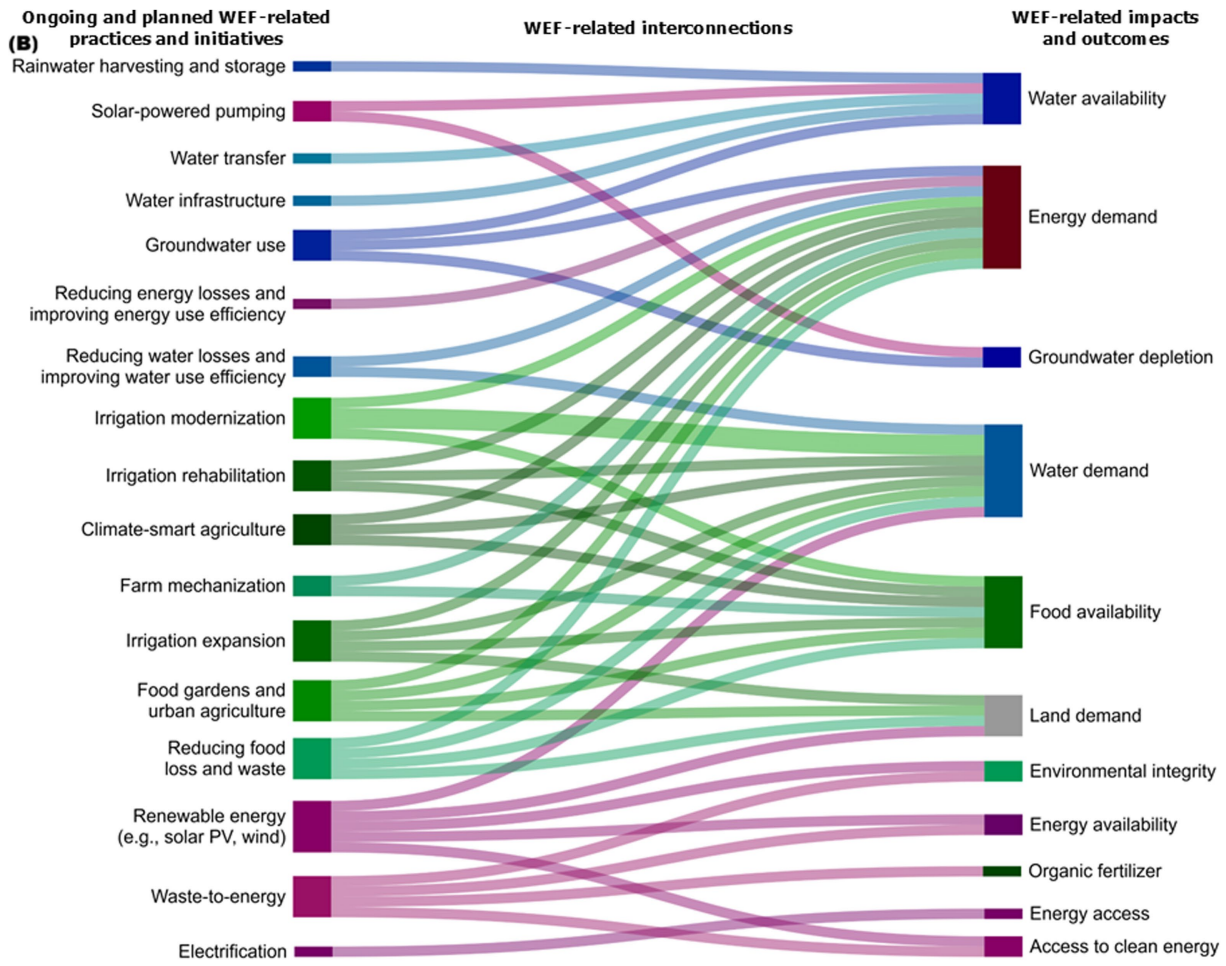


FIGURE 9
(a) An abstract WEF nexus perspective to ongoing and planned WEF-related practices and initiatives in Inkomati-Usuthu Water Management Area (South Africa), showing the interconnections, impacts, and outcomes. Sources: expert key stakeholders; (MDEDT, 2011; GoSA, 2012; DAFF, 2015; DNAEconomics, 2016; Eskom, 2017; DWS, 2018a; GoSA, 2019; IUCMA, 2019; Balzer, 2020; DTIC, 2020; GoSA, 2020; MPG, 2020; DWS, 2021; EDM, 2021; IUCMA, 2021; Nyamadzawo, 2021; AfricanEnergyChamber, 2022; DALRRD, 2022; DEDT-MPG, 2022; DTIC, 2022; DWS, 2022a; EDM, 2022a; EDM, 2022b; IUCMA, 2022b; MDARDLEA, 2022; MPG, 2022a; MPG, 2022b; Nyamadzawo, 2022; DWS, 2023; EDM, 2023; Drawn in SankeyMATIC: https://sankeymatic.com/; Colours depict the source of interconnections). **(b)** An abstract WEF nexus perspective to ongoing and planned WEF-related practices and initiatives in Mzingwane Catchment (Zimbabwe), showing the interconnections, impacts, and outcomes. Sources: expert key stakeholders; (LIMCOM et al., 2017; GoZ, 2018; Dickens et al., 2020; GoZ, 2020a; GoZ, 2020b; ZERA, 2021; AfricanEnergyChamber, 2022; GoZ, 2022c; GoZ, 2022a; GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022e; GoZ, 2022j; GoZ, 2022k; ZERA, 2022; ZimVAC and FNC, 2022d; GoZ, 2023a; ZERA, 2023; SNV, 2025; Drawn in SankeyMATIC: https://sankeymatic.com/; Colours depict the source of interconnections).

in 2024, South Africa would have saved about 13,351.7 GWh, which is sufficient to support about 22 million indigent households with basic electricity for a whole year at 50 kWh per household per month (GoSA, 2003).

4.3.7 Nexus-based planning and implementing the deployment of renewable energy for multiple gains

About a decade ago, South Africa initiated the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) as a competitive tender process to facilitate private sector investment into grid-connected renewable energy (RE) generation (Eberhard and Naude, 2016). With at least 104 Independent Power Producers (IPPs) having reached financial close to date with a total capacity of 7,825 MW, at least 90 of these IPPs have started commercial operations, and they have delivered about 6,180 MW of electricity capacity to the grid (DMRE, 2025). To date, the operational IPPs have generated 126,201 GWh, enough to power more than 38 million households in South Africa, and have accrued several social, economic and environmental benefits. To date, these multidimensional benefits include employment opportunities for South African citizens (construction and operations), actual contribution realised for socioeconomic development, actual contribution realised for enterprise development, shareholding by black South Africans, shareholding by local communities, offsetting carbon dioxide (CO_2) emissions and water savings of 86,531 job years, ZAR3.3 billion, R1.0 billion, 38.3, 8.4%, 128.1 Mton CO_2 and 151.4 million kilolitres, respectively (DMRE, 2025).

5 Limitations of the study

While the six WEF indicators in the iWEF tool and their dimensions may not be representative of all such out there, these were selected and used in previous and current version(s) of the iWEF tool due to their suitability and relevance at different scales in the southern Africa region (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b). It is acknowledged that the current version of iWEF model (December 2025) used in this study includes a subset of domains of resource security for water (availability, use/utilisation), energy (accessibility, use) and food (productivity, sufficiency). Still, it excludes others for water (accessibility, stability, affordability), energy (sufficiency, reliability, affordability, energy type), and food (accessibility, affordability, stability, utilisation; Ang et al., 2015; Miller, 2017; Mabhaudhi et al., 2019; Nhamo et al., 2020a). However, resource availability at a higher level (e.g., national, international) is no guarantee for access at a local scale (e.g., household), and vice versa. Accessibility and connection to networks of service do not guarantee a consistent, reliable, and stable supply, and the latter are critical to the WEF nexus, especially in developing regions. Resources must be available, and people must have the means to access them. A household can be connected to the mains supply network for water and electricity, but still spend extended periods without service due to water rationing and electricity load shedding, which undermines WEF resources security. At the household level, household water insecurity occurs when any of the four domains of water security (availability, accessibility, use, and stability) are not present (Young et al., 2021). Thus, the current set of six indicators in the iWEF tool and their dimensions may mask other issues critical to resource security, including the affordability of resources or services, the reliability of supply, or resource quality, which may affect interpretation. For example, accounting for surface water quality significantly worsens current and future water scarcity compared to considering water quantity aspects only (Jones et al., 2024).

Despite this limitation, the current version of the iWEF tool is envisaged as a good starting point for assessing the WEF nexus in the southern Africa region and the Global South, and for further improvement. The operating principle of the iWEF model, i.e., the AHP, is often criticised for its subjectivity. However, the AHP technique provides a structured approach to systematically process and transform the inescapably subjective and personal preferences of an individual or a group into objective measures for decision-making (Saaty and Vargas, 2012b; Canco et al., 2021). The AHP has found application in many fields and various specialities that face multicriteria problems requiring the aggregation of distinct indicators and the monitoring of performance for benchmarking, policy analysis, and decision-making (Triantaphyllou and Mann, 1995; Nhamo et al., 2020a). The AHP technique allows for the engagement and active participation of stakeholders, which is one of the founding principles of the WEF nexus approach (Beekma et al., 2021). This engagement of stakeholders in the AHP-based iWEF tool potentially addresses uncertainty, the use of quantitative data from established databases addresses data accuracy and quality issues, while the use of less than nine (9) criteria or factors (i.e., WEF-related indicators) and calculation of the consistency ratio (CR) in the iWEF tool ensures consistency of stakeholder pairwise judgements (Nhamo et al., 2020a). While indicator or weight changes might influence results, a key limitation in this study is the lack of sensitivity analysis; however, previous studies showed that the AHP method is robust and has acceptable sensitivity (Yaraghi et al., 2015).

6 Conclusions and recommendations

We assessed the state of the WEF nexus using mixed-methods at the catchment and water management area scales in southern Africa, with the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe) serving as case studies. The state of the WEF nexus, including security and management of WEF resources, is moderately sustainable and unbalanced in the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe). This is evidenced by frequent water outages/rationing, the incidence of waterborne diseases (e.g., cholera), frequent electricity load shedding, hunger and malnutrition, trade-offs between coal and gold mining and the land-water-environment, and unsatisfactory progress in achieving the SDGs.

The WEF nexus varies spatially and temporally, and there is a need for developing localised analysis and contextual interventions. While both case study areas should first prioritise the water sector for intervention, this should be followed by the energy and food sectors in the Inkomati-Usuthu Water Management Area, and vice versa in the Mzingwane Catchment. At the indicator level, a stark contrast is the need to prioritise cereal productivity least in the Inkomati-Usuthu Water Management Area and most in the Mzingwane Catchment, respectively. While ongoing and planned interventions such as promotion of renewable energy, dam construction and improving resource efficiency show considerable potential for improving resource securities, planning and prioritisation of these and other interventions in the two case studies need to apply a nexus approach for understanding and managing potential economy-wide opportunities and risks of implementation and scaling from a nexus perspective, with due consideration of decentralised solutions for off-grid contexts. Thus, the iWEF model is useful for bringing together WEF stakeholders to establish a baseline state of the WEF nexus and status of implementation of the approach at multiple scales, which is an opportune platform for co-planning, harmonising activities among the WEF sectors, crafting strategies for improving WEF resources security for all and accelerating achievement of SDGs.

In the future, promising integrated WEF solutions, such as wastewater reuse, solar-powered agrivoltaics, and floatovoltaics, require piloting to demonstrate and measure their multisectoral impacts in the real world, informing the accelerated implementation of the WEF nexus approach for sustainable development. Future WEF nexus studies in the Inkomati-Usuthu Water Management Area (South Africa) and the Mzingwane Catchment (Zimbabwe) should give due consideration to the climate, environmental, and health nodes of the nexus. The six indicators in the iWEF model fail to give a comprehensive picture of the quality of WEF resource security, and it needs to be broadened to include other pertinent indicators, such as those for resource quality and reliability of supply. Preferably, the iWEF model should be further improved to enhance flexibility and adaptability regarding the number and nature of indicators.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by Humanities and Social Sciences Research Ethics Administration, University of KwaZulu-Natal, South Africa. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CT: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. AS: Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. HM: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. GJ: Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. TM: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2026.1768279/full#supplementary-material

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