Implementing the water–energy–food nexus through tools and scenario planning: a case study approach for southern Africa

Cuthbert Taguta

221089062

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Bioresources Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.



Dr Aidan Senzanje

Date: 17/04/2025



Prof Tafadzwanashe Mabhaudhi

Date: 17/04/2025

DECLARATION OF PLAGIARISM

I, Cuthbert Taguta, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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Cuthbert Taguta (Student Number: 221089062)

Date: 17 / 04 / 2025

DECLARATION OF PUBLICATIONS

The following are the list of publications in this thesis.

Taguta, C, Nhamo, L, Kiala, Z, Bangira, T, Dirwai, T L, Senzanje, A, Makurira, H, Jewitt, G P W, Mpandeli, S, Mabhaudhi, T. 2023. A geospatial web-based integrative analytical tool for the water-energy-food (WEF) nexus: the iWEF 1.0. *Frontiers in Water 5*. DOI: 10.3389/frwa.2023.1305373.

Taguta, C, Senzanje, A, Kiala, Z, Malota, M and Mabhaudhi, T. 2022. Water-energy-food nexus tools in theory and practice: a systematic review. *Frontiers in Water 4*. DOI: 10.3389/frwa.2022.837316.

The following Manuscripts are under preparation and are set for submission to journals:

1. A people-centred and data-informed methodological framework and guidelines for co-developing integrated water–energy–food (WEF) nexus scenarios
   Taguta, C, Senzanje, A, Makurira, H, Jewitt, G P W, Dirwai, T L, Mabhaudhi, T
2. Status of implementation of the water-energy-food nexus approach at sub-national scales: case of South Africa
   Taguta, C, Senzanje, A, Makurira, H, Jewitt, GPW, Kiala, Z, Bangira, T, Dirwai, TL, Mpandeli, S, Nhamo, L, Mabhaudhi, T
3. Status of implementation of the water-energy-food nexus approach at sub-national scales: case of Zimbabwe
   Taguta, C, Senzanje, A, Makurira, H, Jewitt, GPW, Kiala, Z, Bangira, T, Dirwai, TL, Mpandeli, S, Nhamo, L, Mabhaudhi, T

The following papers were presented at national and international conferences and trainings:

1. 25th WaterNet/WARFSA/GWP-SA Symposium "Enhancing Sustainability: Upscaling Innovations and Best Practices for Integrated Catchment and Water Resources Management (ICWRM) in Eastern and Southern Africa – Leaving No One Behind". 30th October - 1st November 2024 (Avani Maseru Hotel, Maseru, The Mountain Kingdom of Lesotho). **Title of presentation**: Co-developing integrative water-energy-food (WEF) nexus scenarios.
2. Water-Energy-Food (WEF) Nexus Advanced School for SADC Region. 13-17 August 2024 (Future Africa Campus, University of Pretoria, South Africa). **Title of presentation**: A people-centred and data-driven methodological framework and guidelines for co-producing water-energy-food (WEF) nexus scenarios.
3. Water-Energy-Food (WEF) Nexus Advanced School for SADC Region. 13-17 August 2024 (Future Africa Campus, University of Pretoria, South Africa). **Title of presentation**: Theory and application of iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical modelling tool.
4. Water-Energy-Food (WEF) WEF Nexus Advanced School for MENA Region. 4-8 February 2024 (The Hashemite University, Zarqa, Jordan). **Title of presentation**:

Introducing iWEF 1.0: A geospatial web-based integrative analytical tool for the water-energy-food nexus: the iWEF 1.0.

5. 25th International Congress on Irrigation and Drainage. 01-08 November 2023, Visakhapatnam, India. International Workshop of Working Group on Water-Food-Energy Nexus (WG-WFE_N) "The Water-Energy-Food-Nexus: Implementation and Examples of Applications". Paper #06. **Title of paper**: Status of implementation of the water-energy-food (WEF) nexus approach: case of South Africa and Zimbabwe.
6. Water-Energy-Food (WEF) Nexus Winter School 14-18 August 2023 (Pretoria, South Africa). **Title of presentation**: Introducing iWEF 1.0: A web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool.
7. 23rd WaterNet/WARFSA/GWP-SA Symposium on Integrated Water Resources Management for Sustainable Development in Eastern and Southern Africa 2022 (Sun City, South Africa). **Title of presentation**: Towards Co-producing Water-Energy-Food (WEF) Nexus Futures.
8. Water-Energy-Food (WEF) Nexus Winter School 8-12 August 2022 (Pretoria, South Africa). **Title of presentation**: Introducing iWEF 1.0: A web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool.

In all the above papers and manuscripts, the conceptualization of the idea was done by C Taguta (student), and A Senzanje, T Mabhaudhi, H Makurira and GPW Jewitt (supervisors). The geospatial web-based integrative analytical tool for the water-energy-food nexus (iWEF) developed in this work is a further development and improvement of a spreadsheet-based integrative analytical model for the water-energy-food nexus. C Taguta conducted the research and the write up while the supervisors corrected and proof-read the manuscripts.

Signed: 

Cuthbert Taguta (Student Number: 221089062)

ABSTRACT

To develop tools and avail evidence for promoting implementation of the integrated transformative water-energy-food (WEF) nexus approach in southern Africa, this study assessed the status of existing WEF nexus tools, developed and applied a WEF nexus analytic tool, and developed a WEF nexus scenario-based methodological framework and guidelines. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol was used to review literature on the status of existing WEF nexus tools. Despite the relative abundance (46 by 02 of July 2021) of reported WEF nexus tools, the broader accessibility, uptake, and utility of their majority (61%) is limited by their unavailability and limited functions.

The geospatial web-based and Analytic Hierarchy Process (AHP)-based integrative analytical tool for the WEF nexus (the iWEF) was developed using digital tools, and calibrated and validated with existing tools and data at varying spatio-temporal scales. The iWEF model was used with inputs (pairwise comparison matrices, PCMs) from key WEF-related expert stakeholders to assess the state of WEF nexus and implementation of the approach at sub-national scales in southern Africa, specifically Inkomati-Usuthu Water Management Area and Ehlanzeni District Municipality (South Africa) and Mzingwane Catchment and Umzingwane District (Zimbabwe). It was found that the state of the WEF nexus is moderately sustainable in Inkomati-Usuthu Water Management Area, Ehlanzeni District Municipality, Mzingwane Catchment and Umzingwane District due to suboptimal integrated WEF nexus composite indices (maximum = 0.286) of 0.209, 0.210, 0.189 and 0.194, respectively. This is due to the unbalanced management and insecurity of WEF resources that is apparent in the two catchments and two ditsricts. Mining for coal (South Africa) and gold (Zimbabwe) and climate change threatens the WEF nexus in the four studied areas. Using evidence from literature review and input from key WEF-related expert stakeholders, and established framework development protocols, this study developed, refined and validated generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

In conclusion, the majority of relatively abundant WEF nexus tools are fraught with functional limitations and the iWEF tool is reliably applicable across multiple scales. Implementation and state of the WEF nexus approach is moderately sustainable in southern Africa and the developed methodological framework and guidelines for co-developing integrated WEF nexus

scenarios are robust. This study recommends the demand-driven improvement of the iWEF tool, and methodological framework and guidelines, and their application in case studies to facilitate implementation of the WEF nexus approach towards robust and resilient WEF systems.

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My sincere gratitude to the stakeholders from Mzingwane Catchment (Zimbabwe National Water Authority; Matabeleland South Provincial Government Departments for Agriculture, Irrigation, Energy, Environment and Meteorology; Agricultural Extension Workers; Farmers) and Umzingwane District in Zimbabwe for discussing with me the water-energy-food issues in their areas.

I owe my gratitude to the developers (Luxon Nhamo, Tafadzwanashe Mabhaudhi, *et al.*,) of the first version of the iWEF (a geospatial web-based integrative analytical tool for the water-energy-food nexus) model. Their work was the foundation for my work, and they provided me with advice. My gratitude to Jeremiah Taguta and Zolo Kiala whose programming skills were useful in developing the iWEF tool.

I owe sincere gratitude to my family for their steadfast prayers, encouragement, inspiration, patience, long-suffering, unconditional, love, and warmth.

DEDICATIONS

Dedicated to:

My wife **Sheila**,

My children **Tawananyasha**, **Shalom** and **Shekinah**, and

My parents **Jealous** and **Lucia**.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
ABM	Agent-based modelling
AEZs	Agro-ecological zones
AGRITEX	Department of Agricultural Technical and Extension Services (Zimbabwe)
AHP	Analytic Hierarchy Process
AHP-OS	AHP Online System
AI	Artificial intelligence
AIRDP	Accelerated Irrigation Rehabilitation and Development Plan (Zimbabwe)
AMD	Acid mine drainage
AU	African Union
AUC	African Union Commission
AWEFSM	Agricultural Water-Energy-Food Sustainable Management
BAU	Business-as-usual
BFAP	Bureau for Food and Agricultural Policy
BP-DEMATEL-GTCW	Back Propagation neural networks–DEcision MAking Trial and Evaluation Laboratory–Game Theory Combination Weight
BRAHEMO	BRAhmaputra HydroEconomic Model
CALFEWS	California Food-Energy-Water System
CAPRI	Common Agricultural Policy Regionalised Impact
CER	Centre for Environmental Rights
CI	Consistency index
CityGML	City Geography Markup Language
CLEWs	Climate-, Land-, Energy- and Water-systems
CMIP	Coupled Models Intercomparison Project
CO_2	Carbon dioxide
COGTA	Cooperative Governance and Traditional Affairs
COMESARIA	Common Market for Eastern and Southern Africa Regional Investment Agency
CP	Crop productivity
CR	Consistency ratio
CRD	Centre for Reviews and Dissemination

CSIR	Council for Scientific and Industrial Research
CSS	Cascading Style Sheets
CV	Coefficient of variation
DAFF	Department of Agriculture, Forestry and Fisheries
DAFNE	Decision-Analytic Framework to explore the water-energy-food NExus
DDM	District Development Model
DEA	Department of Environmental Affairs
DM	District Municipality
DMRE	Department of Mineral Resources and Energy (South Africa)
DOI	Digital object identifier
DSSAT	Decision Support System for Agrotechnology Transfer
DTIC	Department of Trade, Industry and Competition (South Africa)
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation (South Africa)
EA	Energy accessibility
EDM	Ehlanzeni District Municipality
EP	Energy productivity
EPA	United States Environmental Protection Agency
EPAT	Energy Portfolio Assessment Tool
ESMAP	Energy Sector Management Assistance Program
EU	European Union
FAO	The Food and Agriculture Organization of the United Nations
FEWCalc	Food-Energy-Water Calculator
FNC	Food and Nutrition Council
FPC	Farm Performance Calculator
FSF	Food self-sufficiency
FSIN	Food Security Information Network
GAEZ	Global Agro-Ecological Zones
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GIS	Geographic information system
GNAFC	Global Network Against Food Crises
GoSA	Government of South Africa

GoZ	Government of Zimbabwe
GPS	Global positioning system
GREAT for FEW	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus
GCMs	Global climate models
GCWM	Global Crop Water Model
GSG	Global Scenario Group
GWP-SA	Global Water Partnership Southern Africa
GUI	Graphical user interface
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HLPE	High Level Panel of Experts
HTML	HyperText Markup Language
IBMR-MY	Indus Basin Model Revised-Multi Year
IAMs	Integrated Assessment Models
IEA	International Energy Agency
INCA	Integrated Catchment Model
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IPPPP	Independent Power Producers Procurement Programme
IRENA	International Renewable Energy Agency
ITEEM	Integrated Technology-Environment-Economics Model
IUCMA	Inkomati-Usuthu Catchment Management Agency
IUWMA	Inkomati-Usuthu Water Management Area
iWEF	The geospatial web-based integrative analytical tool for the WEF nexus
IWRM	Integrated Water Resources Management
JET	Just Energy Transition
LBPTC	Limpopo Basin Permanent Technical Committee
LEAP	Low Emissions Analysis Platform
LED	Light-emitting diode
LIMCOM	Limpopo Watercourse Commission
LM	Local Municipality
LNG	Liquefied natural gas

LPJmL	Lund-Potsdam-Jena model
LPG	Liquefied petroleum gas
macOS	Mac operating system (Apple)
MC	Mzingwane Catchment
MCDM	Multi-criteria decision-making
MDARDLEA	Mpumalanga Department of Agriculture, Rural Development, Land and Environmental Affairs
MDEDT	Mpumalanga Department of Economic Development and Tourism
MDB	Municipal Demarcation Board (South Africa)
MEA	Millennium Ecosystem Assessment
MIFCP-WEFN	Multi-level Interval Fuzzy Credibility-constrained programming Water-Energy-Food Nexus
MPG	Mpumalanga Provincial Government
MS	Microsoft
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
NDCs	Nationally determined contributions
NDP2030	National Development Plan 2030 (South Africa)
NDS1	National Development Strategy 1 (Zimbabwe)
NeFEW	Nexus of Food, Energy, and Water
NEST	Nexus Solutions Tool
NGOs	Non-governmental organisations
NO_x	Nitrous oxides
NPC	National Planning Commission (South Africa)
NRW	Non-revenue water
NSL	Negotiation Simulation Laboratory
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Co-operation and Development
OGC	Open Geospatial Consortium
OSeMOSYS	Open Source energy MOdeling SYStem
p(P>500)	Probability of exceeding 500 mm of rainfall (%)
P_{annual}	Annual rainfall (mm)
P_{length}	Length of rainfall season (days)
PCC	Presidential Climate Commission

PCM	Pairwise comparison matrix
PICOS	Population, indicator, comparison, outcome and study design
PRIMA	Platform for Regional Integrated Modeling and Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVOUT	Average daily specific photovoltaic power output
RAP	Representative Agricultural Pathway
RCP	Representative Concentration Pathway
REDZs	Renewable Energy Development Zones
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RI	Random consistency index or Random index
RIASCO	Regional Interagency Standing Committee
SADC	Southern African Development Community
SDG	Sustainable Development Goal
SDM	System Dynamics Modelling
SE4ALL	Sustainable Energy for All
SEI	Stockholm Environment Institute
SES	Social-ecological systems; socio-ecological systems
SEWEM	System-wide Economic-Water-Energy Model
SIM4NEXUS	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe
SNV	Stichting Nederlandse Vrijwilligers (Foundation of Netherlands Volunteers)
SO_2	Sulphur dioxide
SPHY	Spatial Processes in Hydrology
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathway
Stats SA	Statistics South Africa
SVM	Support vector machine
SWAT	Soil and Water Assessment Tool
SWIM	Soil and Water Integrated Model
T_{max}	Maximum temperature
TV	Television
UCEC	Urban Circular Economy Calculator

UD	Umzingwane District
UFOP	UNION ZUR FÖRDERUNG VON OEL- UND PROTEINPFLANZEN E.V.
UK	United Kingdom
UN	United Nations
UN-DESA	United Nations, Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UN-Habitat	United Nations Human Settlements Programme
UNECE	United Nations Economic Commission for Europe
UNEN	United Nations Economist Network
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNGA	United Nations General Assembly
USA	United States of America
WA	Water availability
WEAP	Water Evaluation And Planning system
WEC	World Energy Council
WEF	Water-energy-food
WEFO	Water, Energy and Food security nexus Optimization
WEFSiM	Water-Energy-Food Nexus Simulation Model
WEST	Water Economy Simulation Tool
WHAT-IF	Water, Hydropower, Agriculture Tool for Investment and Financing
WMA	Water management area
WMO	World Meteorological Organization
WoGA	Whole of Government Approach
WP	Water productivity
WRC	Water Research Commission
WWTWs	Wastewater treatment works
ZERA	Zimbabwe Energy Regulatory Authority
ZESA	Zimbabwe Electricity Supply Authority
ZimStat	Zimbabwe National Statistics Agency
ZimVAC	Zimbabwe Vulnerability Assessment Committee
ZINWA	Zimbabwe National Water Authority

ZPC	Zimbabwe Power Company
ZRB	Zambezi River Basin

LIST OF SYMBOLS AND UNITS

Abbreviation/Symbol	Meaning
°C	Degree Celsius
GWh	GigaWatt hour
Ha	Hectare
kg CO_2-eq/kg	Kilogram of carbon dioxide equivalent per kilogram
kg/kWh	Kilograms per kiloWatt-hour
kg/ha	Kilogram per hectare
km^2	Square kilometres or kilometres squared
kWh	KiloWatt-hour
kWh/kWp	KiloWatt-hour per kiloWatt peak
kWh/m²	KiloWatt-hour per square metre
ℓ	Litre
ℓ/c/d	Litres per capita per day
ℓ/kWh	Litres per kiloWatt-hour
ℓ/kWhSO	Litres per kiloWatt-hour sent out
M	Metre
m/d	Metres per day
m/s	Metres per second
m^3/d/km	Cubic metres per day per kilometre
m^3/per capita/yr	Cubic metres per capita per year
Mm	Millimetres
Mm^3	Million cubic metres
Mm^3/annum	Million cubic metres per year
mm/yr	Millimetres per year
ML	Megalitres
ML/d	Megalitres per day
MW	MegaWatt
ppm CO_2 eq	Parts per million carbon dioxide equivalent
US$GDP/$m^3$	United States dollars per cubic metres
US$GDP/MJ	United States dollars per megajoule
ton/ha	Tonnes per hectare
W/m^2	Watts per square metre

1 INTRODUCTION

1.1 Water-Energy-Food (WEF) Resources Security

Without secure water, global energy and food needs cannot be met (FAO, 2018). Water, energy, and food (WEF) resources are fundamental to developmental growth and sustenance for everyone's health, dignity, and prosperity (Amer *et al.*, 2017; Leal Filho *et al.*, 2018). Together with land, these strategic resources sustain livelihoods and catalyse economic development (DWS, 2018). Beekma *et al.* (2021) used individual definitions for water, food, and energy security to define collective WEF security as a condition whereby "everyone, everywhere has enough good quality food, access to sufficient water of acceptable quality for health, livelihoods, production and ecosystems while having uninterrupted availability of energy sources at an affordable price coupled with acceptable level of water risk and energy failures".

1.2 Commitments and Progress Towards Universal Access to WEF Resources

In the spirit of securing WEF resources for all, nations made commitments at different levels of government, including visions and policy frameworks. The latter contain strategies, plans and programs outlining priority actions for achieving the desired WEF resource security ambitions, goals, and targets. At the global level, these commitments include the United Nations General Assembly (UNGA) Resolutions (UNGA, 1948) and the 2030 Agenda for Sustainable Development. The latter includes Sustainable Development Goals (SDGs) for water (SDG #6 - clean water and sanitation), energy (SDG #7 - affordable and clean energy) and food (SDG #2 - zero hunger), among others (UNGA, 2015). In Africa, overarching continental commitments to WEF security for all include the African Charter on Human and Peoples' Rights and related resolutions (AU, 1981) and the 50-year Agenda 2063 (The Africa We Want) (AUC, 2015), to mention a few. At the regional level in the Southern African Development Community (SADC) region, overarching regional commitments include the Vision 2050 (SADC, 2020) among others, accompanied with sectoral commitments for the water, energy, agriculture and food. In addition to being party to the above-mentioned global, continental, and regional commitments, countries such as South Africa and Zimbabwe have made their own commitments to universal WEF security in their sovereign national constitutions, and policy frameworks including visions, policies, strategies, and plans. Thus,

states are compelled within their capacity to guarantee everyone the right to adequate supplies of safe water, clean energy, and nutritious food (UN, 2023).

However, despite these noble ambitious commitments, the WEF insecurity crisis persists, while progress in achieving SDGs is slow if not deteriorating at all levels and scales (Sachs *et al.*, 2023). Many people are still hungry, using unclean energy and without water for basic survival, with no guarantee for improved WEF resources security and livelihoods in the future under increasing populations and changing climates (FAO *et al.*, 2022; IEA, 2022; UN, 2023). This calls for pausing and reflecting on (i) actions that were taken to realise these global, regional, and national WEF ambitions and commitments, (ii) how the actions were pursued, so that we can (iii) inform transformative approaches that can accelerate the achievement of SDGs and WEF resource security for all.

1.3 Conventional Approaches to Resources Management Contribute to WEF Insecurity

For a long time, society has used conventional approaches to improve the security of WEF resources and achieved intended objectives while intentionally or unintentionally sacrificing other linked objectives. Practical examples include biofuels production in sub-Saharan Africa which worsened food security due to competition for water and land between biofuels and food (Gasparatos *et al.*, 2012; Sekoai and Yoro, 2016; Kiggundu *et al.*, 2017; Subramaniam *et al.*, 2019; Subramaniam *et al.*, 2020; Kinda, 2021). Sectoral water and energy interventions in the agriculture sector around the world led to increased water and energy consumption, groundwater overexploitation and depletion, and environmental degradation (Smith *et al.*, 2023). Thus, governments have realised that conventional sectoral approaches are ineffective, inefficient, and wasteful, and fail to address the challenges of WEF insecurity, poverty, inequality, unemployment, and poor service delivery (SADC, 2016; GoZ, 2020; NPC, 2020). Thus, planning of WEF systems in silos will probably intensify the competition, trade-offs, risks, and scarcity of resources, and is not an option if society is to secure adequate WEF resources for all in the future (FAO, 2017a; Trisos *et al.*, 2022). Sectoral and linear approaches have reached their limit and there is a need to think outside and beyond sectoral boxes for integrated and sustainable development, utilization, and management of resources (de Loë and Patterson, 2017; Nhamo and Ndlela, 2021; DWS, 2024).

1.4 The Water-Energy-Food (WEF) Nexus Approach

About 90% of global power generation is water intensive (Sivakumar, 2021). Primary energy production and electricity generation accounts for about 10 - 15% of total global water withdrawals, 3% of total global water consumption, and 75% of industrial water withdrawals (HLPE, 2017; FAO, 2018; UN, 2023). On the other hand, drinking water and wastewater management consumes approximately 4% of global electricity supply (FAO, 2018). Agriculture is the major water user globally, regionally, and locally, consuming about 70% globally (85 - 88% in Africa), and about 85% of withdrawn water resources are consumed in irrigated agricultural production (Rost *et al.*, 2008; FAO, 2018; Ringler *et al.*, 2023). Agriculture is the single-largest polluter (non-point- and point-source) of surface water and groundwater through soil erosion, salinification, salinization, sedimentation/siltation, process effluents, and by the excessive use/misuse of agricultural inputs (e.g., agrochemicals) (FAO, 2017b; Mateo-Sagasta *et al.*, 2018). The food production and supply chain consume about 30% of global energy (FAO, 2018; Sivakumar, 2021). About 2-7% of global cropland is used for biofuels production (Popp *et al.*, 2016; UFOP, 2021; Biofuels International, 2022). Agricultural biomass contributes more than 30% of global household energy for heating, cooking, and lighting (Saleem, 2022; Kumar *et al.*, 2023). Irrigated agriculture uses approximately 20% of all cultivated agricultural land, and accounts for about 40% of agricultural production and 60% of cereal production (World Bank, 2022; Ringler *et al.*, 2023). Rainfed farming produces 60% of the world's food on 80% of the cultivated land (FAO, 2022). Thus water, energy and food systems are deeply entwined in a web of interconnections called the water-energy-food (WEF) nexus (IRENA and FAO, 2021), and the current triple crises of WEF insecurity requires planning of integrated solutions at all levels to facilitate scaling (FAO, 2022).

Water, energy, and food are inextricably and concomitantly linked in a WEF nexus such that actions in one sector influence the others either synergistically (mutually beneficial outcomes) or adversely (trade-offs, conflicts - which may potentially include non-optimal outcomes), at different levels and scales (Hoff, 2011; WEF, 2011). The WEF nexus approach highlights the interconnections and interdependence of water, energy and food security and the ecosystems or natural resources that support resource security, that is water, soil, and land (Hoff, 2011; Carmona-Moreno, 2021). The WEF nexus approach seeks to systematically manage the competition for resources in multiple sectors through confronting complex synergies (benefits and co-benefits) and trade-offs (damages, cross-purposes) between development pathways and

options that seek different goals under contested values and interests of people, prosperity, and the environment (Trisos *et al.*, 2022; UN, 2023). Among the various definitions of the WEF nexus presented in literature, this study adopts those presented in this paragraph for the WEF nexus concept, approach and guiding principles.

In its three dimensions, namely conceptual framework, analytical tool, and for discourse (Keskinen *et al.*, 2016; Nhamo *et al.*, 2020a), the WEF nexus has progressed significantly. For example, various conceptual frameworks have been proposed and developed, and they attempt to simplify understanding of WEF interconnections to promote coherence in policymaking (Rasul, 2012; FAO, 2014). These include, among others, the water, energy and food security nexus framework (Hoff, 2011), the system diagram for risks associated with the water-food-energy nexus (World Economic Forum, 2011a) and the energy-food-natural resources continuum: system challenge (World Economic Forum, 2011b). In the discourse space, the WEF nexus has gained the attention of policymakers, for example in regional policy dialogues (Nexus Resource Platform, n.d.). Some progress has been made in developing models and tools that use quantitative and qualitative methods for identifying, highlighting and addressing the nexus interlinkages (synergies and trade-offs) towards WEF resources security and sustainable development (Bazilian *et al.*, 2011; Dai *et al.*, 2018; Beekma *et al.*, 2021; Caretta *et al.*, 2022). These tools include the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015), an integration of Water Evaluation And Planning system (WEAP) and Low Emissions Analysis Platform (LEAP) (SEI, 2012), the WEF Nexus Index (Simpson *et al.*, 2020; Simpson, 2020; Simpson *et al.*, 2022), and the WEF nexus analytical livelihoods framework (ALF) (Mabhaudhi *et al.*, 2019) which later became the integrative analytical model for the WEF nexus (Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b).

Although it is often presented as an evolution, repackaging and improvement of the more established integrated water resources management (IWRM) approach, the strength of the WEF nexus approach lies in its polycentricity and ability to capture and accommodate multiple dimensions (Carmona-Moreno, 2021; Liphadzi *et al.*, 2021). While IWRM is water-centric by integrating water with other policy objectives, the WEF nexus approach is multi-centric and treats water, energy, and food policy objectives as equally important in their integration (Benson *et al.*, 2015; de Loë and Patterson, 2017; Grigg, 2019). Other key beneficial features of the WEF nexus approach include the consideration of integrated policy solutions, multi-tiered institutions, multiple scales, multistakeholder platforms, economically rational decision-making, cost recovery, securitisation of resources within sustainable development, coherence,

non-linear system analysis and dynamic feedback across WEF systems (Hoff, 2011; Benson *et al.*, 2015; Muller, 2015; Sadeghi and Sharifi Moghadam, 2021; Orimoloye, 2022).

1.5 Problem Statement and Research Questions

Despite the gain in momentum of the WEF nexus concept in all three dimensions, and policy and research agenda, the lack of bespoke systematic tools to address trade-offs involved in the nexus, insufficient knowledge in understanding the WEF interconnections, insufficient empirical evidence, and the lack of sound methods for generating plausible future projections are key challenges to sound operationalisation of the WEF nexus approach (Nhamo *et al.*, 2020a; Naidoo *et al.*, 2021; Caretta *et al.*, 2022). For example, Africa lags in WEF nexus research (Craig *et al.*, 2022) while a majority of previous WEF nexus studies in southern Africa have focused on status quo and status quo ante, and not the future. The information on the nature and effectiveness of nexus-friendly and nexus-smart solutions is limited and uncertainties exist around the scalability of integrated systems (Kerr *et al.*, 2022). Similarly, evidence of successful implementation and improved outcomes emanating from the application of nexus concepts are scarce or rare (Kerr *et al.*, 2022). Many aspects remain unknown on the status and characteristics of existing WEF nexus tools, for example, their ready availability, platforms, types, operating spatial scales, geospatial analytic capabilities, and their use and useability in case studies. Existing tools such as the integrative analytical model for the WEF nexus (Nhamo *et al.*, 2020a) lack key characteristics such as, among others, ready availability and accessibility, user-friendliness, and geospatial analytic capabilities. Thus, this study sought to answer the following questions:

i. What is the status of existing WEF nexus tools with respect to availability, platforms, geospatial analytical capabilities, spatial scales, and case studies?
ii. Can the integrative analytical model for the WEF nexus (Nhamo *et al.*, 2020a), previously the WEF nexus analytical livelihoods framework (ALF) (Mabhaudhi *et al.*, 2019), be further developed into a computer-based model with geospatial analytic capabilities?
iii. What is the state of the WEF nexus at selected sub-national scales in southern Africa, specifically in South Africa and Zimbabwe?
iv. How can WEF nexus scenario planning be applied for planning robust and resilient WEF systems in southern Africa, specifically in South Africa and Zimbabwe?

1.6 Research Objectives

The general aim of this research was to develop and apply tools for supporting assessment and implementation of the WEF nexus approach at sub-national scales in southern Africa.

1.6.1 Specific objectives

This study sought to fulfil the following specific objectives:

i. To assess the status of WEF nexus tools with respect to availability, platforms, geospatial analytical capabilities, spatial scales, and case studies.
ii. To further develop the capabilities of the MS Excel based integrative analytical model for the WEF nexus (Nhamo *et al.*, 2020a) into a free access web-based and GIS-enabled application.
iii. To evaluate the state (status quo ante and status quo) of WEF nexus at sub-national scales in southern Africa, specifically in South Africa and Zimbabwe.
iv. To propose and develop a generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

1.7 Thesis Outline

This thesis is structured as follows: Chapter 2 presents a review on the status of existing WEF nexus tools and answers Specific Objective (i); Chapter 3 presents and discusses the development and testing of the iWEF (geospatial web-based integrative analytical tool for the water-energy-food [WEF] nexus) model answering Specific Objective (ii); Chapters 4 and 5 present the application of iWEF model in assessing state of WEF nexus at sub-national scales in South Africa and Zimbabwe, respectively, answering Specific Objective (iii); Chapter 6 presents the development of a people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios answering Specific Objective (iv); while Chapter 7 provides the conclusions and recommendations. The flow of the thesis objectives is shown in Figure 1.1.

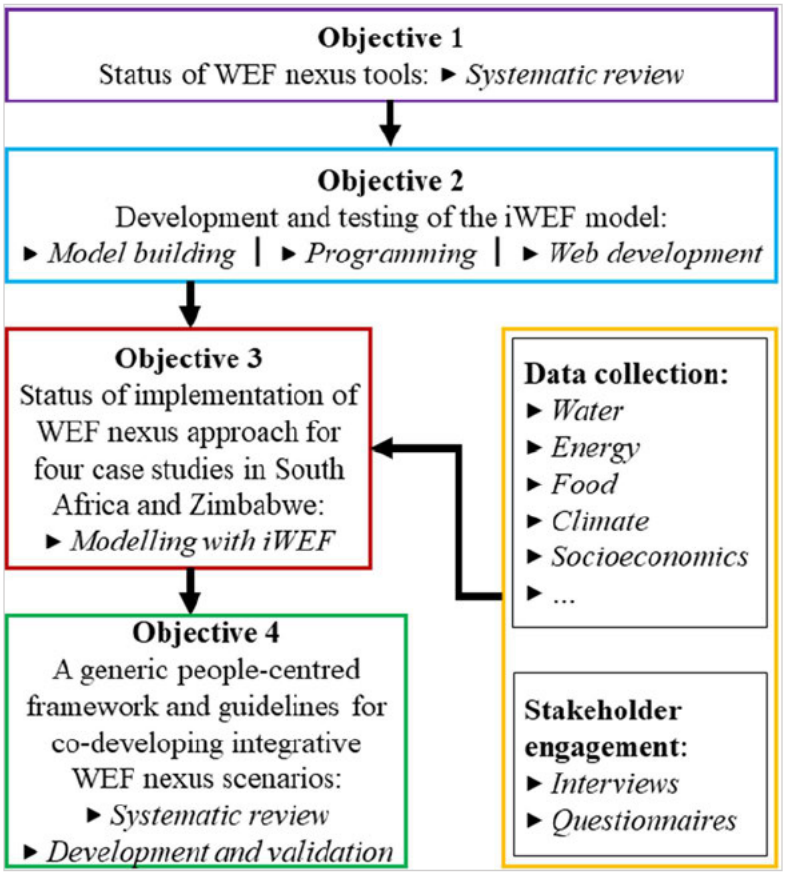


Figure 1.1: Thesis objectives map

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2 WATER-ENERGY-FOOD (WEF) NEXUS TOOLS IN THEORY AND PRACTICE: A SYSTEMATIC REVIEW

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Abstract

Sector-based resource management approaches partly contribute to the insecurities in water, energy and food sectors and resources. These approaches fail to acknowledge and capture the interlinkages between these connected resources, a key strength in the water-energy-food (WEF) nexus approach. However, the multi-centric, multidimensional, and spatiotemporally dynamic WEF nexus is complex and uncertain, thus requiring dedicated tools that can unpack it. Various sources have blamed the slow uptake and practical implementation of the WEF nexus on the unavailability of appropriate tools and models. To confirm those claims with evidence, literature on WEF nexus tools was searched from Scopus and Web of Science and systematically reviewed using the PRISMA protocol. It was found that the WEF nexus tools are being developed increasingly, with a current cumulative number of at least 46 tools and models. However, the majority (61%) are unreachable to the intended users. Some available tools are in code format, which can undermine their applicability by users without programming skills. A good majority (70%) lack key capabilities such as geospatial features and transferability across spatial scale and geographic scope. Only 30% of the tools are applicable at local scales. In contrast, some tools are restricted in spatial scope and scale of application, for example, ANEMI 3 and WEF models for global and household scales, respectively. Most (61%) of the tools lack wide application in actual case studies; this was partly attributed to the tools not being readily available. Thus, efforts should be made to disseminate and ensure end-users' uptake and application of developed tools. Alternatively, user-friendly tools should be developed on-demand as requested and inspired by potential clients. Developers should consider utility, transferability and scalability across uses and users when improving existing tools and developing new tools so that they are adaptable, only requiring new, specific location-adapted inputs and data. This will require cautious balancing between tool complexity and simplicity, with some emphasis on flexibility. Where and when it

is necessary to capture spatial dynamics of the WEF nexus, tools should be geographic information system (GIS)-enabled for automatic WEF nexus location selection, geospatial mapping, and visualization. Such GIS-enabled WEF nexus tools can provide a bird's eye view of hotspots and champions of WEF nexus practices.

Keywords: case study, GIS, model, platform, scale, water-energy-food nexus

2.1 Introduction

Water, energy, food, and land drive economic and social development. These strategic resources are degrading and over-exploited by, among many factors, population growth, economic development, dietary shifts, urbanization, pollution, as well as changes in culture, technology, and climate (Mabhaudhi *et al.*, 2016). Projections for the near and distant future expect increased demand for water, energy, and food (Hoff, 2011; IRENA, 2015; Martinez-Hernandez *et al.*, 2017; Tashtoush *et al.*, 2019; Schull *et al.*, 2020). The insecurities of these key resources are further amplified by the disconnected policies and sector-focused approaches to resources management, which ignore the resource interlinkages, coexistence and transboundary nature (Leck *et al.*, 2015). Integrated management of the resources that underpin the water, energy and food security avoid the unintended effects of sector-based approaches to unlock the potential for achieving the Sustainable Development Goals (SDGs) (de Andrade Guerra *et al.*, 2021). This has led to the pursuit of the water-energy-food (WEF) nexus approach as a holistic, integrated approach to managing natural resources that was proposed in the Bonn 2011 Nexus Conference for WEF Security Nexus Solutions for the Green Economy (Leck *et al.*, 2015; Schull *et al.*, 2020). Water, energy and food are inextricably and intrinsically linked in ways that actions in one sector influence the others, synergistically or often adversely, at different levels and scales (Hoff, 2011; IRENA, 2015). The WEF nexus has gained undivided attention in the agenda of research, policy dialogue and development (Bazilian *et al.*, 2011; Eftelioglu *et al.*, 2017). This has seen WEF nexus being mainstreamed into thematic areas, strategies and policies by local, regional, and international institutions, governments, and organizations (SADC, 2016; GWP-SA, 2019a; GWP-SA, 2019b). The actual nature and significance of interconnections between the WEF resources are context-specific, hence the need to explore and understand the interdependence of water, energy and food security and the natural resources that underpin their security (Liu *et al.*, 2017; Salam *et al.*, 2017). Despite the hype of the WEF nexus agenda, several authors concur that the actual translation of the theory

into practice is lagging hence the need to investigate the limited uptake of the promising approach which is reportedly attributed to inadequate analytical tools and lack of empirical evidence (Byers, 2015; Daher and Mohtar, 2015; Liu *et al.*, 2017; Galaitsi *et al.*, 2018; McGrane *et al.*, 2019; Nhamo *et al.*, 2020a; Naidoo *et al.*, 2021).

Several WEF nexus tools, framings and frameworks have been developed and applied to support enhanced understanding and evaluation of WEF interconnections for ultimately informing integrated planning and decision making (Albrecht *et al.*, 2018; Shannak *et al.*, 2018; Rosales-Asensio *et al.*, 2020; Purwanto *et al.*, 2021). A WEF nexus tool is an intellectual construct of relationships, including mathematical, that simplify and represent reality, and capture WEF spatial and/or temporal interconnections, dynamics and feedback (McCarl *et al.*, 2017; Wicaksono *et al.*, 2017; Albrecht *et al.*, 2018; Saundry and Ruddell, 2020). The criteria for a WEF nexus tool include, among others, cross-sectoral (WEF), cross- disciplinary (WEF), systems focus, integration, analytics, quantitative and/or qualitative, innovation, context, collaboration, policy and implementation (Wicaksono *et al.*, 2017; Albrecht *et al.*, 2018; Dai *et al.*, 2018; Shannak *et al.*, 2018; Rosales-Asensio *et al.*, 2020). WEF nexus tools were previously reviewed on several characteristics, including feedback analysis, optimization and visualization (Wicaksono *et al.*, 2017; Wicaksono and Kang, 2019), informing policy (Shannak *et al.*, 2018) as well as entry requirements, exits and analytical capabilities (Rosales-Asensio *et al.*, 2020). Mannan *et al.* (2018) reviewed analytical features of WEF nexus tools, while Dai *et al.* (2018) focused on model types, spatial scale, purpose and nexus challenge level. Dargin *et al.* (2019) delved on the complexity of WEF nexus tools, while Flammini *et al.* (2014), IRENA (2015), Kaddoura and El Khatib (2017) and Shinde (2017) reviewed their suitability, analytic modelling capabilities, inputs, and outputs. Reviews by Albrecht *et al*. (2018) and Zhang *et al*. (2018) included concepts and methodologies in the WEF nexus and tools.

These previous studies usually reviewed less than ten different WEF nexus tools to provide useful information on the characteristics of different WEF nexus tools. They also overlooked other significant characteristics that may undermine the applicability of these tools. Such characteristics or criteria include availability, platforms, application scales, geospatial analytic capabilities and previous use, among others. WEF relevant elements vary substantially across locations, including resources endowments, constraints and interconnections, thus WEF nexus modeling endeavours must recognize, represent and articulate the inherent heterogeneity across locations (McCarl *et al.*, 2017; Dargin *et al.*, 2019). Eftelioglu *et al.* (2017) and Hiloidhari *et al.* (2017) highlighted that geospatial analytic capabilities in WEF nexus tools solve spatial

decision problems because WEF nexus tools and geographic information system (GIS) are complementary. GIS is a computer-based information system and spatial decision-making tool that supports the precise assessment of distributed WEF resources, thereby addressing economic and environmental goals (Johnson, 2009; Janipella *et al.*, 2019). Thus, GIS-enabled WEF nexus tools assist in providing a bird's eye view for analysis, comparison and identification of WEF nexus hotspots and champions, with the possibility of exploring impacts of interventions and transfer of good practices and technology (Daher and Mohtar, 2015; Fernandes Torres *et al.*, 2019; Lin *et al.*, 2019). WEF nexus tools and GIS can be integrated through 'hard-linking' and 'soft-linking'. The former effectively automates the exchange of input and output data between the WEF nexus and GIS for analysis, mapping, and visualization. 'Soft-linked' coupling requires the user to manually prepare and transfer information, which is cumbersome and somehow prone to error but sometimes allows users to ensure the quality of data and information prior to transfer (Eldrandaly, 2007; Ramos, 2019). The status of geospatial analytic capabilities in existing WEF nexus tools is unknown and needs to be addressed. While geospatial capabilities are not a panacea to analyses, they are useful for allowing analyses at different spatial scales as applicable and visualization of results in a way that is easier for users and decision-makers to understand and utilize. Also, the trend in models nowadays has been to add the geospatial analytic functionality so that users have an option to use it if they need to. However, the functionality of such geospatial analysis enabled tools in small scale cases may be limited by system boundaries and poor spatial resolution of certain data.

The WEF nexus field is rapidly evolving, and it is expected that many new tools were developed in addition to those previously reviewed and more will still be developed. Some critical issues on the characteristics of WEF nexus tools remain vague. For example, what is the general historic and current trend in developing WEF nexus tools? How accessible are the tools that have been developed and reported by other users (Byers, 2015)? Is there a lack of WEF nexus tools and, is it justified? What are they likely to find if a user (new or old) searches online for WEF nexus tools? What are the platforms of existing WEF nexus tools? Can the existing WEF nexus tools handle spatial data to characterize the WEF nexus spatially? If yes, how are geospatial capabilities incorporated in existing WEF nexus tools? What are the least and most popular WEF nexus tools in case studies? Thus, there is a need for an updated review of WEF nexus tools to clarify WEF nexus tools' status and trends of development, their availability and accessibility, platforms, spatial scale of application, geospatial capabilities and

their application in previous case studies. The global aim of this study was to provide a review of the state-of-the-art of WEF nexus tools and their suitability in supporting the implementation of the WEF nexus approach. To fulfil this aim, this study sought to systematically review the available literature and potentially address the following specific objectives to:

i. assess the historic and current trends in the development of WEF nexus tools;
ii. provide an inventory/compendium of existing WEF nexus tools;
iii. review the availability, platforms, spatial scales of application, and geospatial analytic capabilities of existing WEF nexus tools; and
iv. assess the previous application of existing WEF nexus tools in case studies.

This review will serve as an update and guide (until 02 July 2021) for new and old users on existing WEF nexus tools and a starting point for present and future developers who intend to improve existing or create new WEF nexus tools. Secondary to this and without necessarily comparing WEF nexus tools, this review is intended to be a knowledge synthesis to guide and inform interested users of WEF nexus tools on what tools to use under different contexts. This will enhance the quick, easy and effective selection of WEF nexus tools for different conditions and requirements in facilitating the implementation of the WEF nexus approach.

2.2 Materials and Methods

This study conducted a WEF nexus tools systematic review by mapping broad literature to answer questions regarding development trends, availability, platforms, spatial scales, geospatial analytic capabilities, and case studies. These characteristics were excluded in previous reviews which focused on concepts, methodologies, complexity and analytical capabilities (McCarl *et al.*, 2017; Wicaksono *et al.*, 2017; Albrecht *et al.*, 2018; Shannak *et al.*, 2018; Dargin *et al.*, 2019). Although geospatial tools are useful for certain but not problems and situations, interested users need to be guided and informed on status of geospatial analytical capabilities in existing WEF nexus tools. The review was done stepwise, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher *et al.*, 2009), which assist in systematically searching, identifying, and selecting articles on search platforms and reviewing them through appraisal and synthesis of research evidence (Grant and Booth, 2009). Page *et al.* (2021a) and Page *et al.* (2021b) went on to update, further explain and elaborate PRISMA, which was also applied by Fernandes Torres *et al.* (2019) in reviewing literature for proposing a systematic procedure of the nexus concept. The PRISMA

flow diagram was conveniently generated with the user-friendly open-access R package and ShinyApp for PRISMA Flow Diagram[1] by Haddaway *et al.* (2021b), as recommended by Page *et al.* (2021a). The PRISMA steps involved, among others, eligibility criteria, information sources, search strategy, screening, selection, data collection, defining data items, and analysis.

2.2.1 Eligibility criteria

The study used the population, indicator, comparison, outcome and study design (PICOS) strategy, which limits the number of irrelevant articles (Tacconelli, 2010; Methley *et al.*, 2014) (Table 2.1).

Table 2.1: The adapted PICOS strategy used for literature searching

PICOS	**Description**
Population	WEF nexus
Indicator	WEF nexus tools, models, applications
Comparison	N/A
Outcome	Applicability characteristics of WEF nexus tools
Study designs	Qualitative, quantitative and mixed

The PICOS strategy informed the search strategy and the subsequent inclusion-exclusion criteria. Given that the WEF nexus is a fairly novel area of research, broad eligibility criteria were adopted for publications mentioning the development and application of WEF nexus tools. In this regard, only studies with named and operational WEF nexus tools were included, excluding anonymous and non-operational tools.

2.2.2 Information sources and search strategy

The potentially relevant studies in the literature were searched using the same search criteria within two online literature databases, Scopus[2] and Web of Science Core Collection (WoS CC)[3] (until 02 July 2021). These two multidisciplinary databases were selected for their comprehensive coverage and high-quality scientific publications that allow systematic review.

[1] https://estech.shinyapps.io/prisma_flowdiagram/; https://doi.org/10.5281/zenodo.5082518
[2] https://www.scopus.com/
[3] http://www.webofknowledge.com/

Their journal coverage is also remarkably greater than other common databases, even in natural science and engineering disciplines. In addition, citation searches were conducted in reviews to identify WEF nexus tools and their corresponding publications that could be missed in Scopus and WoS databases, including those by international organizations such as Food and Agriculture Organization (FAO) and International Renewable Energy Agency (IRENA). The search criteria in the two databases (Scopus and WoS CC) involved searching topics using Boolean expressions. The search topics were formed from the keywords "nexus, tool, model, application, spatial, map, geographic information system, GIS", together with iterations of "water, energy, food" and WEF. The details of the search topics used are presented in Table 2.2.

Table 2.2: Search topics for retrieving documents related to WEF nexus tools in Scopus and WoS CC

Search topic (first row)	**Search topic (second row)**	**Search topic (third row)**
(water-energy-food) OR (water-food-energy) OR (energy-food-water) OR (energy-water-food) OR (food-energy-water) OR (food-water-energy) OR WEF OR WFE OR EFW OR EWF OR FEW OR FEW	AND nexus	AND (tool OR model* OR application OR "geographic information system" OR gis OR geospatial OR spatial OR map* OR web)

Consideration was given to peer-reviewed papers (articles, reviews), scientific book chapters, papers from proceedings and materials from special issue editorial material, institutional documents including dissertations, theses, or technical papers, all written and published in English. The WEF nexus approach, tools and integration of geospatial features are still novel. Thus, the date of publication, geographic scope, journal disciplines and impact factors were kept open to capture all WEF nexus tools and versions, from earliest to latest by the time this work was carried out (until 02 July 2021). All records obtained from Scopus, WoS, and citation searches were combined to facilitate the removal of duplicates.

2.2.3 Screening and selection of studies (inclusion and exclusion criteria)

In line with the objectives of this systematic review, the titles, abstracts, and keywords of the searched studies were reviewed and screened for selection. The screening was in favour of publications on (i) WEF nexus tools that have an operational version(s) instead of proposed or

work in progress, and (ii) capturing at least all three components of the WEF nexus: water, energy, and food. Terms such as 'land' and 'agriculture' were considered a proxy for the food component since it is a key element directly linked to food production. Secondly, books and chapters that replicated some published journal articles were excluded. Eventually, the eligible papers were retrieved for review. Although these eligible papers and sources may not include all the WEF nexus literature out there, they best represent the previous work relevant to addressing and fulfilling our research questions and objectives.

2.2.4 Collecting data

A data extraction sheet was designed in simple, flexible, and functional MS Excel based on the study objectives. Key data on the selected papers were extracted from the eligible studies and organized in the data extraction sheet. These were organized in columns by the tool's characteristics, including acronym, authors/developers, year of initial development, availability, platform, the spatial scale of application, geospatial capabilities, and the number of previous case studies. The sub-columns for availability contained general availability, web availability, and dead links. The sub-columns were web applications, desktop applications, code, Excel, serious games and unknown. The sub-columns under spatial scale of application presented five classes namely (i) global, (ii) continental / economic region / basin / transboundary, (iii) country / national, (iv) provincial / sub-basin / catchment, and (v) local including sub-catchment / municipal / city / town / household / project. The sub-columns under number the case studies column included three classes according to frequency, namely low (one to three), moderate (four to 10), and high (more than 10).

2.2.5 Data items and analysis of studies

The characteristics of the WEF nexus tools used in this study were criteria briefly defined and described (Table 2.3) from previous related reviews (Flammini *et al.*, 2014; IRENA, 2015; Shinde, 2017; Dargin *et al.*, 2019) as well as author's discretion and synthesis.

Table 2.3: Definitions of characteristics of WEF nexus tools

Tool characteristics	**Description**
WEF system tool (herein synonymous with model, application)	An intellectual construct of mathematical relationships capturing the spatial and/or temporal dynamics and feedback between food, energy, and water systems. A WEF nexus tool describes a system's structure and function to give insights into select attributes of physical, biological, economic, or social dimensions and dynamics of a WEF system (EPA, 2009; Saundry and Ruddell, 2020).
Availability	The quality or state of presence, ready reachability, and accessibility by public users[4].
Web availability	The quality or state of being available at a specific expected internet or online location[5].
Broken or dead links	A hyperlink on a web page that no longer works, maybe because the destination web page no longer exists or has been moved or error[6].
Platform	A hardware or software used to host an application or service, that serves as a foundation on which outside parties can access or build complementary products or services (Tiwana, 2014)[7]. For this study, the platform is the form or type of the tool which includes web applications, desktop applications, codes, Excel worksheets, and serious games/simulators[8].
Web application (or web app)	An application program usually hosted on a remote server and accessible through web-browsers (Bourne, 2014; Sturm *et al.*, 2017).
Desktop application (or desktop app)	An application that runs stand-alone and locally on a computer device such as a desktop or laptop[9].
Code	The symbolic arrangement of data or instructions in a computer program or the set of such instructions[10].
Excel worksheet or spreadsheet	A collection of cells organized in rows and columns that keeps and manipulates data[11].
Serious game	A "learning by playing" decision-based platform, including role plays, that allows policymakers to play out scenarios and see what would bring the best outcome (Vamvakeridou-Lyroudia *et al.*, 2017; Saundry and Ruddell, 2020).
Unknown	When the form or characteristic of the tool is not stated by the developers, previous users or literature[12].

[4] https://blog.amplexor.com/website-availability-what-is-it
[5] https://blog.amplexor.com/website-availability-what-is-it
[6] https://www.techopedia.com/definition/23236/broken-link; https://www.computerhope.com/jargon/b/broken_link.htm
[7] https://www.techtarget.com/searchitoperations/definition/platform
[8] https://dictionary.cambridge.org/dictionary/english/format; https://www.collinsdictionary.com/dictionary/english/format
[9] https://encyclopedia2.thefreedictionary.com/desktop+application
[10] https://www.thefreedictionary.com/computer+code
[11] https://www.excel-easy.com/basics/worksheets.html
[12] https://www.merriam-webster.com/dictionary/availability

Spatial scale	The spatial extent or level of application for the tool measured by area, distance or length, including ecological, hydrological and administrative[13] (Dai *et al.*, 2018; Saundry and Ruddell, 2020).
Geospatial capabilities	Spatial mapping, visualization and analysis through the use of either open-source GIS or commercial products and software (Johnson, 2009; Janipella *et al.*, 2019).
Case study (practice)	A published use of the tool in assessing real-life circumstances or simulating and modelling hypothetical scenarios; the application of nexus research to real-world problems (Dai *et al.*, 2018; Saundry and Ruddell, 2020; Vinca *et al.*, 2021).
Low case studies	Refers to previous use of the tool in between one to three areas
Moderate case studies	Refers to previous use of the tool in between four to 10 areas
High case studies	Refers to previous use of the tool in more than 10 areas

All the tool characteristics defined in Table 2.3 are desirable attributes in the intended users' applicability of WEF nexus tools. For example, the availability and accessibility of a WEF nexus tool in the public domain is a key prerequisite to its applicability by the intended users. Thus, tools' links provided by developers and previous users, such as web addresses and digital object identifiers (DOIs), were tested. On encountering broken or dead links, a basic search for the tool was conducted on the tool's related website or Google Search Engine[14]. All evidence of the tools' characteristics was gathered from literature without contacting the authors/developers to avoid bias. The results were presented as tables and charts for analysis, visualization, and interpretation.

2.3 Results and Discussion

The pursuit for the WEF nexus approach has seen the advent of several tools for analyzing, modelling, and simulating the WEF nexus in terms of resource supply, demand, nexus indicators and indices. This section presents the findings from reviewing the searched literature against the characteristics and criteria that was previously presented in Table 2.3.

2.3.1 Literature search

The detailed results of the search and selection process are shown in the flow diagram in Figure 2.1. Initially, 1057, 1185 and 83 records were obtained from Scopus, WoS CC, and citation

[13] https://www.igi-global.com/dictionary/mapping-the-chromosome-through-a-novel-use-of-gis-and-spatial-analysis/43412
[14] https://www.google.com/

searches. Duplicates were removed in EndNote and MS Excel from these records to remain with 1543 papers. The screening and selection of the 1543 studies with the inclusion and exclusion criteria yielded 183 papers that were eventually retrieved for review, whose findings are presented in the succeeding sections.

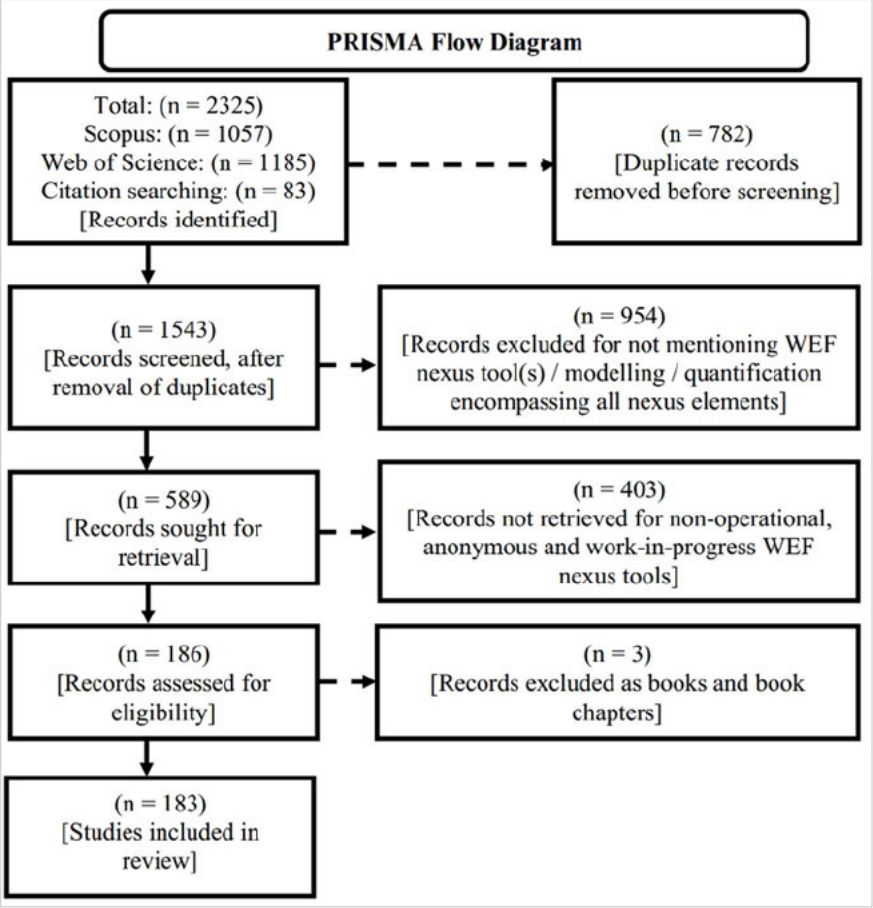


Figure 2.1: The PRISMA 2020 framework and flow diagram for the systematic review, which includes searches of databases and other sources (adapted from Haddaway *et al.* (2021a), Haddaway *et al.* (2021b), Page *et al.* (2021a) and Page *et al.* (2021b))

2.3.2 Trends in development of WEF nexus tools

Overall, reviewing the literature identified 46 WEF nexus tools. From a quantitative perspective, this is quite a large number which contrasts previous reports of lack in WEF nexus tools (Byers *et al.*, 2015; Liu *et al.*, 2017; Nhamo *et al.*, 2020a; Naidoo *et al.*, 2021). Even if no publication date range was imposed during the literature search, Figure 2.2 shows how, among the papers selected and reviewed in this study, the advent of WEF nexus tools started around 2009-2012.

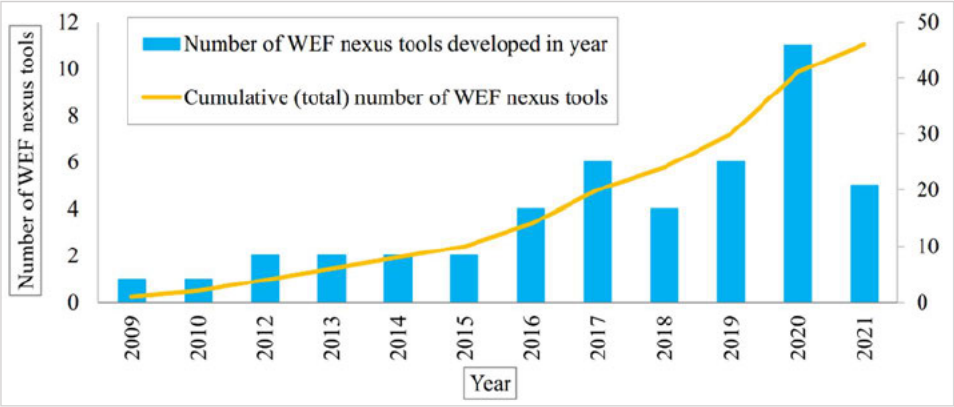


Figure 2.2: Trend in the development of WEF nexus tools (until 02 July 2021)

Generally, the development of new WEF nexus tools has been gaining momentum with time since 2012, as evidenced by the increasing annual trends and cumulative total number with time (Figure 2.2 and Appendix A). The trends of annual increases in developed WEF nexus tools with time testifies to the continuously increasing momentum of the WEF nexus agenda in research and maybe practice. Shinde (2017) also observed this increasing trend, implying that implementing the WEF nexus, which has been lagging, is attempting to catch up with WEF nexus agenda research and dialogues. The progressive trend in WEF tools development is motivated by the increased traction of the WEF nexus concept in international policy and research, including the iconic World Economic Forum Water Initiative (WEF, 2011) and Bonn 2011 Conference on The WEF Security Nexus Solutions for the Green Economy (Hoff, 2011). Interestingly, the rising trends coincide with the adoption of the related SDGs, with the literature showing emphasis on SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy) a few years later in 2015.

From Figure 2.2, the existence of WEF nexus tools such as MuSIASEM (46) and ANEMI (45) pre-2011 shows that the WEF nexus concept predates 2009 (Appendix A). The year 2011 was just a landmark when the concept gained momentum and recognition in wider research and policy agenda circles. The annual rate of development of WEF nexus tools stagnated during 2009-2010, increased in 2012 but stagnated until 2015, increased in 2016-2017 and then fell in 2018, followed by consecutive increases in 2019-2020. The year 2020 boasts of the largest number (11) of developed WEF nexus tools, including NEST (14), iWEF (15) and WEF Nexus Index (16); while an almost half year of 2021 (January to July) recorded five (5) developed

WEF nexus tools. If the past and current trends are anything to go by, more WEF nexus tools are being and will continue to be developed in the future. This will provide researchers, practitioners, non-practitioners, decision- and policymakers with a wide array of tools that they can use to translate the WEF nexus approach from theory to practice. However, this multitude of WEF nexus tools may lead to some confusion in the community, which may require some sort of standardization for the tools that use the same approaches, methods and techniques, as well as those that apply for similar contexts and scales. Instead of continuing to develop new WEF nexus tools, we can use the existing ones with some improvements where necessary and this calls for ready availability and accessibility of the tools and their source codes. What remains to be theoretically and practically investigated are the key characteristics of these reported tools, especially their availability to interested users, their platforms, scales of application (e.g., spatial and temporal), geospatial analytic capabilities, and popularity in practice. Addressing such questions and issues is critical in guiding users to selecting the WEF nexus tools that better suit their case studies and peculiar requirements. The succeeding sections present results of the theoretical assessment of these key characteristics as criteria in reviewing the available literature on WEF nexus tools.

2.3.3 Existing WEF nexus tools

The 46 WEF nexus tools found in the literature are summarized in Appendix A, including their names, developers, year of publication and brief description. The characteristics of the existing 46 WEF nexus tools are presented in Appendix B, which include availability, platforms, spatial scales, geospatial capabilities, and the number of previous case studies.

2.3.4 Availability and platforms of WEF nexus tools

Although availability and accessibility do not necessarily translate to usefulness, it is a necessary prerequisite that allows wide use of WEF nexus tools for improved nexus-friendly decision-making (Byers, 2015; IRENA, 2015). Logically, interested users can only choose from and use tools readily available at their disposal. To add, free availability of WEF nexus tools ensures broader chances of engagement, especially for users without adequate resources to procure costly modelling software in developing countries.

Less than half (39%) of the existing 46 tools are available to public users, despite the abundance of WEF nexus tools that have been developed (Appendix B). The rest (61%) cannot be found in the public domain (Figure 2.3a). This concurs with Vinca *et al.* (2020), who observed that existing WEF nexus tools and data are neither always openly availed nor integrative across the three sectors. Public availability and documentation of tools are imperative for capacity building, knowledge transfer and transparency (Antle and Valdivia, 2021).

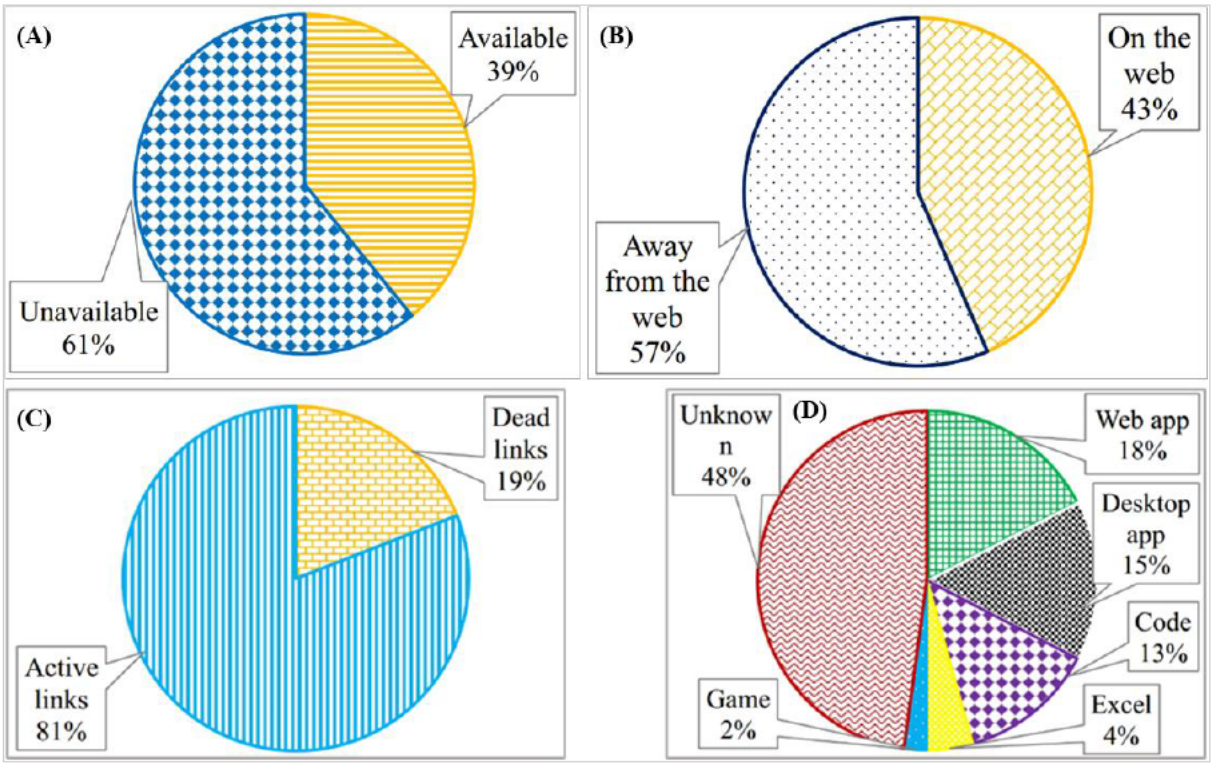


Figure 2.3: Existing WEF nexus tools' (a) general claimed availability, (b) claimed availability in the public domain, (c) confirmed availability on the web, and (d) platforms

Of all the 46 tools, only 43% are supposedly hosted on the public web domain (Figure 2.3b), but reality shows that about a fifth of this category have dead links (Figure 2.3c). They cannot be located where developers and previous users claim them to be or by searching online. These include DAFNE (24), PRIMA (38), WEF Nexus Assessment 1.0 (40), Foreseer (44) and MuSIASEM (46). For example, DAFNE (24) and its interactive portal is only accessible to specific practitioners and non-practitioners from the Zambezi and Omo-Turkana River basins. Sustainable use of WEF nexus tools requires them to be openly accessible so that they can be used in diverse contexts by interested and knowledgeable (but not necessarily expert) users

(Byers, 2015; Keairns *et al.*, 2016; Dargin *et al.*, 2019). The availability of such tools should preferably be at low- to no-cost in resource-poor developing regions (Dargin *et al.*, 2019).

The platforms for the largest portion (≈ 48%) of all existing tools are not stated and unknown (Figure 2.3d). These include AWEFSM (17), WEFSiM (22), WEFO (32), EWF Nexus Tool (39) and Nexus Webs (41). They are automatically not readily available for application in case studies by interested users. For those tools whose platforms were stated or observed, their descending order of prevalence includes web applications, desktop applications, codes, spreadsheets, and serious games.

The major platform is web applications (≈ 18%). These include DAFNE's (24) Negotiation Simulation Laboratory (NSL), whose access is categorically restricted to DAFNE project partners and stakeholders (Melenhorst, 2018). This complicates its use in other case studies outside DAFNE project participants and case study areas, i.e., Zambezi and Omo-Turkana River basins. Others include Q-Nexus (30), WEF Nexus Tool 2.0 (37) and Pardee RAND WEF Security Index (36). Despite their importance as visual portals and platforms providing essential information on the WEF nexus, some web-based tools, including WEF Nexus Index (16) and WEF Discovery Map (1), are just portals that lack essential WEF nexus quantitative analytic capabilities. Interested users can neither input nor analyze their own case study data in these tools; they can only retrieve prepared information on the preloaded case studies. Compared to normative and static tools, predictive WEF nexus tools attract decision and policy makers because they provide test beds for strategies (McCarl *et al.*, 2017).

Desktop applications take the second largest proportion (≈ 15%) of WEF nexus tools. These include CALFEWS (5), NeFEW (6), WEF (29) and NexSym (31). Some desktop application tools such as NeFEW (6) require additional infrastructure such as MATLAB to run, implying the need for programming competence in MATLAB for interested users. The major limitation of these compiled desktop application type of tools is the lack of flexibility in cases where a user may desire to link them with other models or adapt the code for specific study purposes such as interdisciplinary policy analysis (Foster *et al.*, 2017).

Approximately 13% of the tools are codes archived in GitHub and Zenodo online libraries. These include NEST (14), WHAT-IF (20) and ANEMI (45). GitHub[15] is a code hosting platform for project collaboration and version control, while Zenodo[16] is an open dissemination

[15] https://www.w3schools.com/whatis/whatis_github.asp
[16] https://help.zenodo.org/

research data repository. Although the codes are available, which promotes transparency and flexibility for integration and customization, especially for users knowledgeable with programming, they pose difficulty in applying them by the non-professional user because of programming competence requirements and lack of graphical user interface (GUI). According to McCarl *et al.* (2017) and Dargin *et al.* (2019), more interactive and user-friendly tools with output that is easily understood by decision-makers have enhanced usefulness and longevity, and this requires continual dialogue between developers and users.

Approximately 4% of WEF nexus tools are Excel worksheets and in the custody of their developers. These include FPC (9) and iWEF (15) and interested parties must request these worksheets from the authors and developers. This is a potential barrier to their wide application by interested users, depending on the willingness and time taken to share the tool.

Serious games constitute the minority (2%). These simulation games include Nexus Game (28), Serious Game for SIM4NEXUS (25), and MAGIC Nexus Game (46). These and DAFNE's (24) NSL are 'edutainment' tools that offer a safe virtual online environment for negotiating and 'learning by planning' on implications of participants' choices, decisions, and actions in the WEF nexus. They expose players to the interconnections between the WEF resources and sectors, acting as testbeds for policies and thus capacity building in the WEF nexus.

Despite their web availability and analytical capabilities, some tools' applicability is confined to the case study areas developed and tested for. For example, GREAT for FEW (18) is applicable only in Taiwan because it lacks flexibility and key information for other areas from the user's perspective (Lin *et al.*, 2019). The same applies to WEF Nexus Tool 2.0 (37), whose geographical scope was originally developed for Qatar (Daher and Mohtar, 2015). SIM4NEXUS (25) models were specifically developed for the context of European countries (Sušnik *et al.*, 2018). Developing a WEF nexus tool with a specific case study in mind can pose a limit to its applicability in other areas and conditions with different contexts (Byers, 2015).

2.3.5 Spatial scales of application and case studies of WEF nexus tools

WEF nexus tools tend to operate at different scales and perspectives (Byers, 2015). Tools for large spatial scales such as continental, regional, transboundary basin, and national applications dominate, followed by those for medium and local scales (Figure 2.4 and Appendix B).

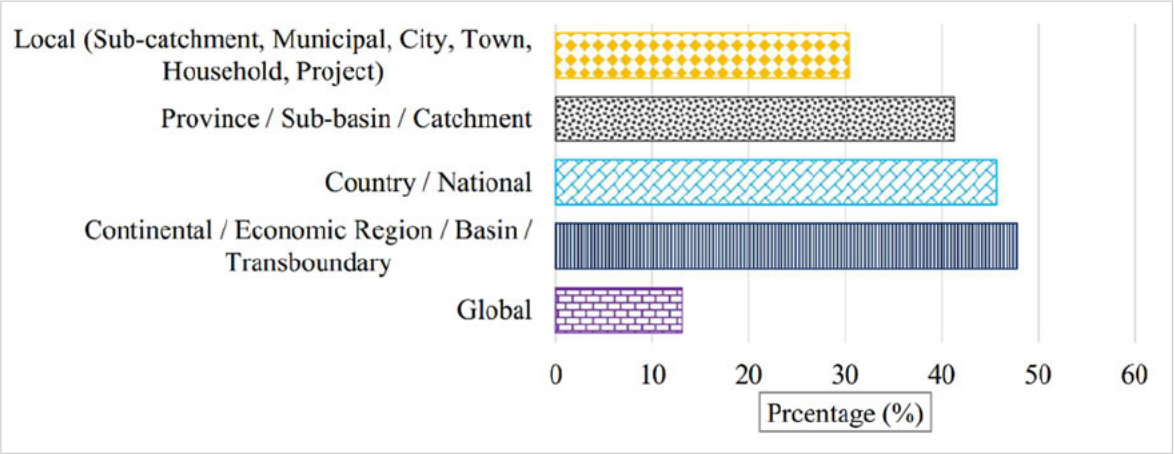


Figure 2.4: Spatial scales of application of documented WEF nexus tools (Dai *et al.*, 2018)

The latter include ANEMI (45), WEF Nexus Index (16) and Pardee RAND WEF Security Index (36). Thus, these large-scale tools are appropriate for aggregate level studies and inform WEF policies and decisions. However, these large-scale tools are inappropriate for local-scale studies. Policy- and decision-makers require WEF nexus insights at different levels of administration, which can be policy- and community-relevant scales, be it national, regional or local scales (IRENA, 2015; Albrecht *et al.*, 2018). This highlights a gap for local-scale tools that can model, simulate and analyze local WEF nexus for assessing challenges, impacts, interventions and adaptation to change that can promote sustainable development at the grassroots level (Terrapon-Pfaff *et al.*, 2018). However, some tools tend to be use-, user-, and scale-selective. For example, ANEMI3 (45), WEF Nexus Tool 2.0 (37) and the WEF model (29) are most appropriate for global, national, and household scales, respectively (Davies and Simonovic, 2010; Daher and Mohtar, 2015; Hussien *et al.*, 2017). EPAT (19) and WEF Nexus Tool 2.0 (37) use energy and food as entry points, respectively, with a potential bias towards those individual sectors and their policies and players in the WEF nexus. Similarly, Byers (2015) reported the existence of a variety of WEF nexus tools that operate at different scales or were developed for specific case studies. This tendency of tools to be specific in application scales, uses and users may limit their applicability in case studies of different scales and contexts. Preferably, WEF nexus tools should be robust, multi-scalar, flexible and adaptable across users, uses, spatial scale and scope, only requiring new, specific location-adapted inputs and data (IRENA, 2015). This flexibility is critical for WEF nexus tools to be adapted to

different contexts and geographies. They can be mandated for utility in and by a wide range of uses and users, respectively (Albrecht *et al*., 2018). For example, the iWEF (15) tool is applicable at regional scale (southern Africa) (Mabhaudhi *et al.*, 2019), national scale (South Africa) (Nhamo *et al.*, 2020a) and local scale (Sakhisizwe Local Municipality) (Nhamo *et al.*, 2020b), respectively. However, developing multi-scalar tools is elusive due to different input data requirements and availability at different scales bound by ecological, hydrological, and administrative boundaries. Similarly, users at different scales and from different sectors have context-specific objectives for nexus analytics which may vary from place to place. To be widely used in implementing the WEF nexus approach, WEF nexus tools should be accessible, especially to developing country analysts, and applicable to finer geographical coverage (Bazilian *et al.*, 2011). For example, WEF nexus tools that are applicable at catchment, provincial, district and local municipality scales can facilitate nexus-based water, energy and irrigation management and service delivery through evidence-based resource planning and decision-making by catchment, water, energy, irrigation and municipality managers (GoZ, 2012; Ringler *et al.*, 2018; COGTA, 2020). Sustainable implementation of the WEF nexus requires open access to relevant tools to readily avail them for use in many contexts across the world by knowledgeable practitioners and non-practitioners (Byers, 2015).

2.3.6 Geospatial analytic capabilities in WEF nexus tools

WEF resource supply and demands are unevenly and unequally distributed in space and time, and thus the spatial disaggregation and comprehensive analysis of their nexus requires WEF nexus tools with geospatial analytic capabilities (Bouzarovski and Petrova, 2015; Luo *et al*., 2020; Simpson *et al.*, 2020; Sun *et al.*, 2020). Sometimes it is necessary to spatially characterize the WEF nexus in cases where and when the phenomena vary in space and location (Eftelioglu *et al*., 2017; Hiloidhari *et al*., 2017). Out of the 46 tools that were reviewed, only less than one-third (≈ 30%) possess geospatial capabilities (Figure 2.5a and Appendix B).

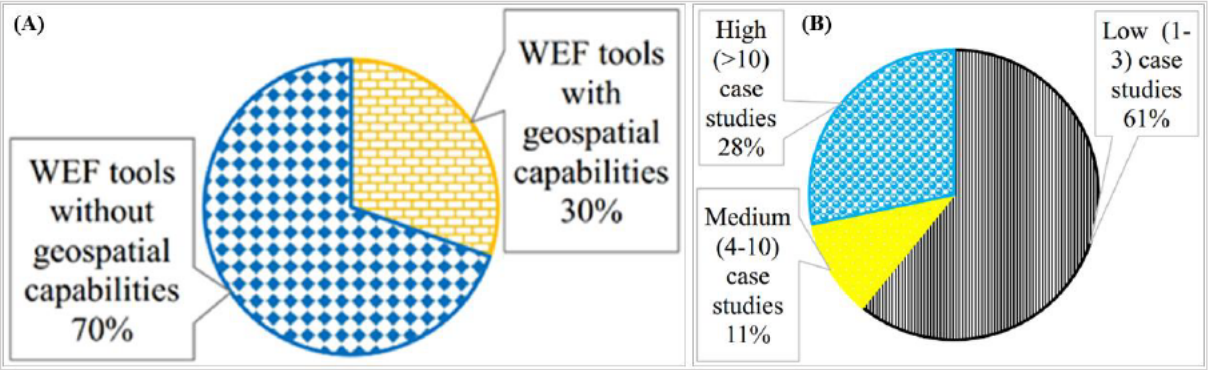


Figure 2.5: Existing WEF nexus tools' (a) geospatial capabilities, and (b) popularity in previous case studies

The rest (≈ 70%) can only aggregate and generalize the WEF nexus in their analyses or display without performing geospatial mapping and visualization the WEF nexus. This majority is useful in situations that do not require the spatial disaggregation of the WEF nexus, for example, in the context of similar distribution of trade-offs and synergies between WEF resources and sectors. Thus, this majority cannot characterize the spatial dynamics of the WEF nexus, which poses a big limitation to the tools because WEF resources are spatially distributed in nature (McCarl *et al.*, 2017; Dargin *et al.*, 2019). This concurs with Shannak *et al.* (2018) and Ravar *et al.* (2020), who reported that even though WEF resources are exposed to intense variations in time and space, most presented models are not spatially disaggregated, which gives rise to deviation from the spatial reality.

WEF resources vary in space and time, thus requiring spatial disaggregation with appropriate tools for comprehensive analysis that can inform improved planning for sustainable management. As much as it is necessary to determine aggregate and average values in WEF nexus analysis, it is equally important to characterize its dynamics in space and time because different areas have different WEF nexus conditions such as resource endowments, utilisation and demands. This spatial characterization can be achieved by running several point measurements and analysis of the WEF nexus, which is time-consuming and tedious. Fortunately, this can be done simultaneously, efficiently, and effectively using geospatial features in some WEF nexus tools, either as built-in or loosely coupled for pre-processors of input datasets and/or post-processors of outputs. Though less common, the former method hard-links geospatial features and the WEF nexus tool such that it is relatively convenient and easier for the user since the GIS-enabled WEF nexus tool automatically exchanges information

and analyses WEF nexus in space, without need for manual preparation and transferring of information between the two systems. The latter mode of soft-linking or loose-coupling requires the user to manually prepare, manipulate, and transfer information between the geospatial tool and the WEF nexus tool, which is inconvenient, tedious, and prone to error by the user. GIS enhances finer spatial detailing of the WEF nexus profile in study areas (Eldrandaly, 2007; Ramos, 2019).

The minority of existing WEF nexus tools that have spatial capabilities, either by "hard-linking' or 'soft-linking', are presented in Table 2.4.

Table 2.4: WEF nexus with geospatial capabilities

Tool	Geospatial features	Mode of GIS integration
WEF Nexus Discovery Map (1)	Base map and hosting through ArcGIS	Hard-linked
ITEEM (3)	Spatial input datasets	Soft-linked
MAXUS (7)	Pre-processing of input datasets	Soft-linked
NEST (14)	Spatial input datasets	Soft-linked
WEF Nexus Index (16)	Global base map	Hard-linked
GREAT for FEW (18)	Base map and input datasets as spatial maps	Hard-linked
Daily Model (23)	Spatial input datasets and satellite-based climatic products	Soft-linked
DAFNE (24)	Spatial input datasets, Geoportal with a dynamic, customizable interactive web map by Web GIS plus customized additional "marker" layer	Hard-linked
SIM4NEXUS (25)	GIS layers for dams' location; GIS layers for digital elevation model	Hard-linked
Q-Nexus (30)	Base map	Hard-linked
PRIMA (38)	Spatial input datasets	Soft-linked
CLEWs (42)	Spatial input datasets	Soft-linked
WEAP-LEAP (43)	Thematic maps (land use), maps of basin	Hard-linked
Foreseer (44)	Spatial input datasets	Soft-linked
MuSIASEM (46)	Spatial input datasets	Soft-linked

Integration of GIS and WEF nexus tools should collectively accomplish pre-processing, spatial analysis, and mapping/visualization, regardless of the integration arrangements of the two systems or sub-systems. Evidence from existing WEF nexus tools with geospatial capabilities

shows that 'soft-linked' WEF nexus tools and geospatial features make use of pre-processing, spatial input datasets, thematic layers, and post-processing. In modular 'soft-linked' integration of the WEF nexus tool and GIS capabilities, the user performs geospatial tasks manually, as shown in Figure 2.6a.

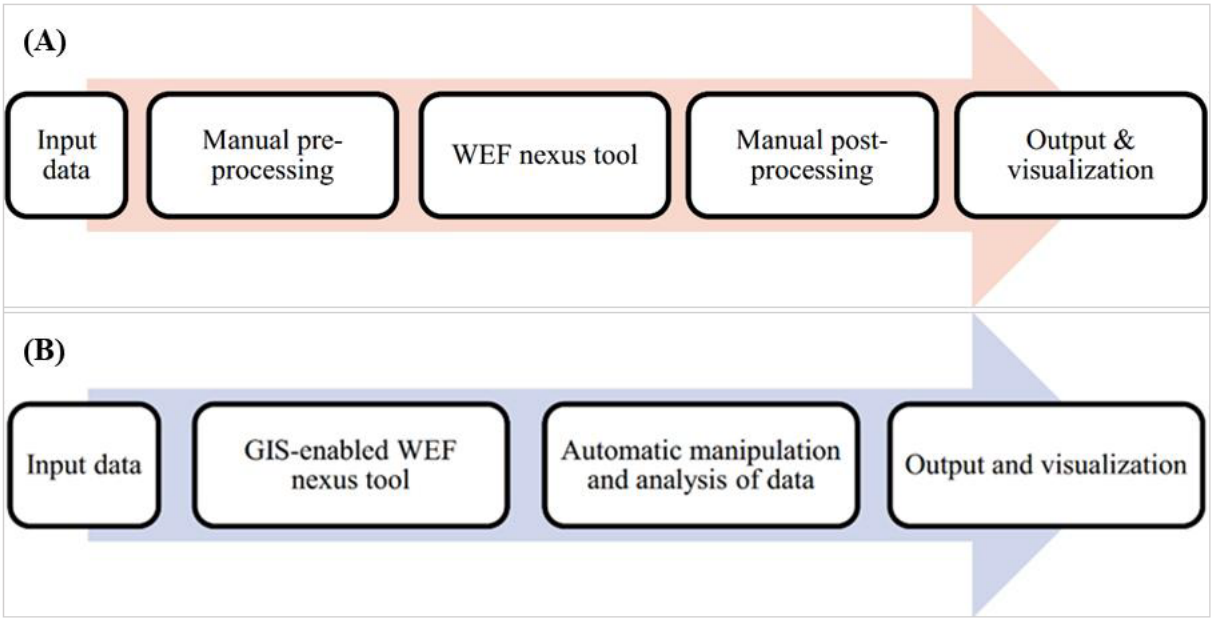


Figure 2.6: (a) Manual operation of 'soft-linked' WEF nexus tool and geospatial capabilities from user's perspective, and (b) mode of operation for 'hard-linked' GIS-enabled WEF nexus tool (adapted from Burger (2018) and Burger and Abraham (2020))

In this modular integration arrangement, the geospatial data may include land use, administrative boundaries, basins, sub-basins, climate change, socioeconomics variables, and WEF nexus variables (Vinca *et al.*, 2020). Other spatial data that may need pre-processing include existing infrastructure, terrain, environmental policy, availability of natural resources, technology-specific siting suitability criteria, land use, land cover, and economic analyses of grid interconnection costs and locational marginal prices (SEI, 2012; Kraucunas *et al.*, 2015).

On the other hand, 'hard-linked' integration with GIS is common in web and desktop applications. 'Hard-linked' WEF nexus tool and GIS operate with automation on behalf of the user, as shown in Figure 2.6b. 'Hard-linked' GIS-enabled WEF nexus tools depict that common techniques for this integration arrangement include the use of WebGIS, base maps, geodatabases, and geoportals. The 'hard-linked' integration allows for flexible web hosting of the tool, locating case study areas, and real-time interaction, mapping, and visualizing spatial

distributions of WEF nexus (Lin *et al.*, 2019; Simpson *et al.*, 2020; Arenas *et al.*, 2021). Other benefits include storing, integrating, and sharing project GIS datasets (Melenhorst, 2018). Thus, geospatial capabilities in WEF nexus tools make it possible to effectively locate suitable sites, and quantify spatial WEF requirements, supply, budgets, and footprints.

Therefore, there is great potential for comprehensive WEF nexus analysis and characterization if more of the reviewed existing WEF nexus tools could be equipped with geospatial capabilities, especially the user-friendly 'hard-linked' integration, accompanied by mechanisms for ensuring quality control during automated data transfer. This tight coupling allows for automated exchange of information within the integrated system of the GIS-enabled WEF nexus tool, thus more convenient and easily applicable. This integration method removes the need for extra commitment in GIS training, data preparation and processing that comes with 'soft-linked' integration of WEF nexus tools and GIS capabilities.

2.3.7 WEF nexus tools in practice

The frequency of case studies for WEF nexus studies can be essential evidence of the practical applicability of the applied tools, especially if various authors applied the tools in different locations and conditions. A majority (≈ 61%) of the existing 46 WEF nexus tools have been used in a few case studies, that is, between one to three applications (Figure 2.5b and Appendix B). Despite showing great potential, most of these tools, including GREAT for FEW (18) and DAFNE (24), were only applied by their developers in the original case studies for which they were developed. Interestingly, some tools that scored medium to high in the frequency of case studies were used in multiple areas by their developers only, with few case studies or none by other authors outside the development team. Such tools include BP-DEMATEL-GTCW (2) and SD-WFE (11) applied in various locations in China (Chen and Chen, 2021) and Iran (Ravar *et al.*, 2020), respectively. The lack of popularity in use can be linked to the fact that they are unavailable. Interested users cannot easily access most tools (Table 2.5), wherein a significant number (10) of the widely used tools are readily available for users. The majority (21) of the tools used in a lower number of case studies are out of ready reach by the interested public users.

Table 2.5: WEF nexus tools, ready availability and their case studies

Low (1-3) case studies		**Medium (4-10) case studies**		**High (>10) case studies**	
Available	**Unavailable**	**Available**	**Unavailable**	**Available**	**Unavailable**
6	21	2	3	10	4
ITEEM (3); WEF-Sask (4); **CALFEWS (5)**; WEF Nexus SD (8); FPC (9); WEF-P (10); **WEST (12)**; MIFCP-WEFN (13); **NEST (14)**; iWEF (15); AWEFSM (17); **GREAT for FEW (18)**; EPAT (19); **WHAT-IF (20)**; K-WEFS (21); WEFSiM (22); Daily (23); DAFNE (24); **UCEC (26)**; ABM-SWAT (27); WEF (29); NexSym (31); WEFO (32); SEWEM (33); BRAHEMO (34); IBMR-MY (35); Nexus Webs (41)		**Q-Nexus (30)**; **WEF Nexus Tool 2.0 (37)**; PRIMA (38); EWF Nexus (39); WEF Nexus Assessment 1.0 (40)		**WEF Nexus Discovery Map (1)**; BP-DEMATEL-GTCW (2); **NeFEW (6)**; MAXUS (7); SD-WFE (11); **WEF Nexus Index (16)**; **SIM4NEXUS (25)**; **Nexus Game (28)**; **Pardee RAND WEF Security Index (36)**; **CLEWs (42)**; **WEAP-LEAP (43)**; Foreseer (44); **ANEMI (45)**; **MuSIASEM (46)**	

Key: Bold = readily available

Thus, the widespread use of WEF nexus tools must be promoted by availing them in the public domain, where they can be accessed without hassles. This regular use by different authors in different locations (i.e., different countries) and conditions can provide the feedback necessary for independent validation, further enhancing and improving tools.

2.4 Limitations of Review

The study adapted a systematic review which sought to systematically search for, appraise and synthesize research evidence, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We acknowledge that a weakness of systematic reviews is that by restricting the search and inclusion criteria, often some literature particularly those reported in traditional research reports or deliverables may be excluded. However, despite that weakness, systematic reviews are still highly regarded because of the transparency in the reporting of its methods, which allows for repeatability of the process. The review analysed WEF nexus literature that was published by 02 July 2021. However, the WEF nexus field is currently commanding widespread attention and witnessing an increased number of publications with time. Thus, it is likely that some WEF nexus tools were developed, improved

and applied between July 2021 and now. This presents a need to update this work and document the WEF nexus tools that were developed and applied after that date.

This assessment ignored the option of contacting the authors or developers of tools, who could have provided more details and clarifications to answer the study questions. However, this was intentional to get the true and unbiased picture of WEF nexus tools in the public literature and the web domain. This was to ascertain what is known and unknown as represented by the available information, whether in its sufficiency or insufficiency. The focus on named tools may have left out some anonymous and general tools. However, their inclusion in this study would be difficult without unique identities. Similarly, tools whose development was proposed or still in progress, such as the Sustainable Development (SD) Calculator (Mosalam and El-Barad, 2020), were left out due to their incompleteness in development and application. The WEF nexus can be broadened to include several other dimensions such as economy, health, environment, nutrition, politics, climate, and land. This is consistent with the water-energy-food-everything (WEF-e) system mentioned by Saundry and Ruddell (2020), with potential for complexity and dimensionality as the number of dimensions and variables increase. Thus, our study focused on tools and models that capture the interlinkages of at least the three basic dimensions of the WEF nexus, that is water, energy and food. However, investigating the actual nature and number of dimensions characterized by the individual WEF nexus tools was outside our scope and is a subject for further study.

2.5 Conclusion and Recommendations

This study sought to assess evidence of WEF nexus tools in theory practice, particularly trends in development, availability, platforms, spatial scales of application and application in case studies. WEF nexus tools are being increasingly developed. By the 2nd of July 2021, there was a cumulative abundance of at least 46 uniquely identified tools dedicated to the WEF nexus. Despite their relative abundance, most developed WEF nexus tools are elusive and unreachable to the public. Thus, developers are encouraged to promote the availability and accessibility of their tools through dissemination. A good starting point is their open deployment on the public web domain, so that the tools can be freely available, applied and rigorously tested. This public deployment will provide users with a wide range of choice of tools for translating WEF nexus theory into practice to fulfil its revered potential, with an opportunity for feedback that can further improve their applicability through practical testing and application. Time, costs, and

human resources could also be saved by using or customizing available tools instead of developing from scratch every time a study is carried out. Building on existing tools would ultimately enhance collaboration and avoid duplication of efforts. The ready availability and ease of accessibility for some WEF nexus tools for potential end-users allows these tools to be applied more easily in nexus-friendly policy- and decision-making processes. Accordingly, some dead and expired links of web-based WEF nexus tools need to be updated, for example, Foreseer (44) and PRIMA (38).

Regarding platforms, developers should strive to deliver WEF nexus tools in convenient, compatible, and friendly forms with a wide range of users in mind, from starters to seasoned. Considerations include minimizing code types of tools requiring users to have programming skills and maximizing web and desktop application tools with user-friendly GUIs. Serious games play a critical role in educating and building capacity on WEF nexus principles and practices. In multi-player mode, these 'edutainment' games can enhance the safe interaction of individuals with each other and the exploration of WEF nexus dynamics and scenarios.

Although no one size WEF nexus tool fits all, developers should consider transferability and scalability for wide utility when improving existing tools and developing new tools. This would ensure that the WEF nexus tools can be applied under various geographic scopes, scales, and conditions without fundamentally changing their structure. Preferably, multi-scalar and local scale relevant tools are needed. Such tools should be flexible and adaptable, only requiring new, specific location-adapted inputs and data. Preferably, WEF nexus tools and models should be developed on-demand as requested by potential clients. Developers need to engage and collaborate with the users in the process, drawing inspiration from the users' needs, expectations, and requirements. This user-inspired design and development is critical to enhance user experience and ensure applicability of the developed tools.

There is a critical mismatch between the requirements of geospatial capabilities in most WEF nexus tools and the dynamic nature of WEF resources whose nexus they are supposed to quantify, analyze, and visually map. Most existing WEF nexus tools are spatially aggregated and lack the essential geospatial capabilities, such as GIS integration, which leads to an unrealistic characterization of WEF nexus dynamics. Only a minority of the tools are integrated to geospatial capabilities, either built-in or loosely coupled for pre-processing input datasets and/or post-processing outputs. Going forward and for improved nexus analytics and visualization, developers of WEF nexus tools also need to harness and integrate the power of

evolving disruptive technological advances including the Internet of Things (IoT), big data, cloud computing, and artificial intelligence (AI) such as machine learning. Future work may need to update and broaden this review and develop a web portal that serves as a "one stop shop" with important information about the characteristics of existing WEF nexus tools. Given the multitude of reported existence of diverse WEF nexus tools, such a platform can inform and guide the WEF nexus community on the attributes of different WEF nexus tools, for example facilitating the selection of WEF nexus tools for use in contextualized objectives and case studies.

Most of the existing WEF nexus tools lack popularity in wide applications. They have been used in a few case studies, mostly applied by their developers in the original case studies for which they were developed. This is caused by unavailability because interested users cannot easily reach and access them. Only by their ready availability can these tools be accessed, used and assessed for actual applicability in different locations and conditions.

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3 A GEOSPATIAL WEB-BASED INTEGRATIVE ANALYTICAL TOOL FOR THE WATER-ENERGY-FOOD (WEF) NEXUS: THE iWEF 1.0

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Abstract

The water-energy-food (WEF) nexus has evolved into an important transformative approach for facilitating the timely identification of trade-offs and synergies between interlinked sectors for informed intervention and decision-making. However, there is a growing need for WEF nexus tools to support decision-making on integrated resources management towards sustainable development. This study developed a geospatial web-based integrative analytical tool for the WEF nexus (the iWEF) to support integrated assessment of WEF resources to support resilience building and adaptation initiatives and strategies. The tool uses the Analytic Hierarchy Process (AHP) to establish numerical correlations among WEF nexus indicators and pillars, mainly availability, productivity, accessibility, and sufficiency. The tool was calibrated and validated with existing tools and data at varying spatio-temporal scales. The results indicate the applicability of the tool at multiple spatial scales from sub-national to regional, highlighting the moderate sustainability in the management of WEF resources at various scales in southern Africa. This is evidenced by the iWEF-based integrated WEF nexus composite indices of 0.185 (Sakhisizwe Local Municipality), 0.155-0.203 (South Africa) and 0.145 (southern Africa) which correspond to a moderate state of the WEF nexus compared to a maximum of 0.286 for high sustainability. The developed iWEF tool has improved the existing integrative WEF nexus analytical tool in terms of processing time and providing geospatial capabilities. The iWEF tool is a digital platform that automatically guides policy and decision-making in managing risk from trade-offs and enhancing synergies holistically. It is developed to support policy and decision-making on timely interventions in priority areas that could be showing signs of stress.

Keywords: modelling, resilience building, resource management, spatial analysis, sustainable development

3.1 Introduction

Water, energy and food are strategic resources that sustain livelihoods and are catalysts for economic development. However, apart from being highly sensitive to climate change, the three resources have been subjected to overexploitation due to the increasing demand from a growing global population and urbanisation (Mabhaudhi *et al.*, 2016; SADC, 2016). At the global level, projections for 2030 and 2050 suggest increased demand of between 40 and 50% for water, 50 and 100% for energy, 50 and 60% for food, and 20% for agricultural land (WEC, 2013; IRENA, 2015; FAO, 2022; UNESCO, 2022). There is, therefore, a need to produce more with limited resources and continue meeting the increasing demand for essential resources from a growing population.

Current water, energy, and food sector-based policies and management practices tend to overlook the intricate interlinkages between the three resources, a scenario that undermines their security as each sector pursues its goals at the expense of the others (IRENA, 2015; Leck *et al.*, 2015). Mabhaudhi *et al.* (2016) highlighted that there is a wealth of WEF nexus information produced in southern Africa, creating opportunities to adopt transformative approaches in sustainable resource management in the region. Current approaches to integrated resources management, while progressive, remain sectoral as they pursue sector policies. For example, integrated water resources management (IWRM) has been criticised for being water-centric (Benson *et al.*, 2015; Grigg, 2019). The IWRM considers water as the entry point, which may lead to trade-offs in other linked sectors, thus triggering inefficiencies of WEF resources utilisation and compromised resource security (Stucki and Smith, 2011; de Loë and Patterson, 2017). This led to the pursuit of alternative approaches that strive for holistic and equitable resources management, including nexus planning (Leck *et al.*, 2015; Schull *et al.*, 2020).

The spectrum of nexus planning includes the water-energy-food (WEF) nexus approach and its various iterations such as food-energy-water (FEW) and energy–food–water (EFW) which inextricably link water, energy and food resources and sectors at multiple scales (Hoff, 2011; Flammini *et al.*, 2014; IRENA, 2015). Although WEF is the most popular framing and configuration, other nexus dimensions linked to these three dimensions and in focus include the environment and human health (Saundry and Ruddell, 2020). However, successful

implementation of integrative approaches such as nexus planning will rely, to an extent, on the availability of tools to analyse and quantify cross-sectoral interactions and identify trade-offs. This requires decision-support tools that support both quantitative and qualitative data as informed by the analysis under consideration, as well as data availability and accessibility (Bazilian *et al.*, 2011; IRENA, 2015). Such decision-support tools include models, and they are useful in informing integrated planning, policy and decision-making.

Previous WEF nexus tools found in the literature are generally complex as they require extensive data input, are selective of spatial scale and geographic scope, and lack feedback analysis, optimisation and visualisation (IRENA, 2015; Kaddoura and El Khatib, 2017; Albrecht *et al*., 2018; Dargin *et al.*, 2019; Rosales-Asensio *et al.*, 2020). Taguta *et al.* (2022c) provide an updated inventory of existing WEF nexus tools, and they found that at least forty-six WEF nexus tools were developed worldwide between 2009 and 2021. However, most of these tools are unavailable (61%), of unknown format (48%), applicable to large scales (70%), lacking in geospatial analytic capabilities (70%), and are relatively unpopular (61%) in application related case studies (Taguta *et al.*, 2022c). For those claimed to be deployed in the public web domain (43%), including web applications (18%) and desktop applications (15%), about 20% were confirmed to be dead links (Taguta *et al.*, 2022c). Some current versions of web-based WEF nexus tools were found to be restricted to specific users (e.g., project partners), spatial scales and scopes for which they were originally developed (Byers, 2015; Taguta *et al.*, 2022c). These inherent restrictions limit the applicability and utility of such promising tools in other contexts and conditions, although it is generally acknowledged that no single univerasal model or tool exists that can cover the entire range of complexities, purposes, priorities, aims, situations, scales and data availability (Wicaksono *et al.*, 2017; Zhang *et al.*, 2018; Dargin *et al.*, 2019; Taguta *et al.*, 2022c). Availability and accessibility are necessary prerequisites for users' broad use of WEF nexus approaches and tools that inform coherent decisions (IRENA, 2015). WEF nexus tools must be applicable at the local level to tailor appropriate solutions for local conditions that leverage synergistic techno-ecological interactions. Preferably, WEF nexus tools should have special attributes that include multi-scalar, and flexibility and adaptability in spatial scale and geographic scope. To bridge the science-policy-practice gap, the WEF nexus approach and tools should be adopted and used by policy and decision-makers to address service delivery, food, energy and water securities, poverty, inequality, and high unemployment, inter alia (Naidoo *et al.,* 2021; Mpandeli *et al.,* 2018; Nhamo *et al.,* 2018).

Since 2015, when the WEF nexus became more pronounced (Liphadzi *et al*., 2021), various attempts have been made to develop a cost and time-effective integrated model to drive the management of the three resources holistically (Albrecht *et al.*, 2018; Botai *et al.*, 2021). The development of such a model that provides numerical relationships is complex as the three resources have different scales and units of measurements (Nhamo *et al*., 2020a). Thus, a WEF nexus model should provide a mathematical construct of relationships between food, energy, and water systems that simplify complex relationships between interlinked sectors and represent management realities by capturing the spatial and/or temporal dynamics and feedback between them. WEF nexus models, therefore, should describe the cross-cutting and integrated relations of the interconnected resources of water, energy and food resources, including the structure and functions to provide an understanding of inherent attributes that impact socio-ecological economic and physical dimensions (EPA, 2009; Saundry and Ruddell, 2020). However, most nexus tools focus on quantitative and qualitative attributes of the linkages, while lacking in spatial attributes that include mapping and visualization. The lack of geospatial elements in existing WEF nexus tools needs to be addressed as WEF resources are spatially distributed (Shannak *et al.,* 2018; Ravar *et al.* 2020). Thus, Geographic Information Systems (GIS) provide a solid platform for WEF nexus tools and can be integrated to simultaneously compute, analyse and map interactions between WEF resources (Eftelioglu *et al.*, 2017).

Although previous studies that include the work of Mabhaudhi *et al.* (2019) and Nhamo *et al.* (2020a,b) developed a novel and dynamic approach that established quantitative relationships between the WEF resources, the tool is Excel-based and lacks a spatial analysis component. It is also unavailable in the public domain where users can access it. This study addresses these gaps by developing a user-friendly Graphical User Interface (GUI) with geospatial analytic capabilities. Thus, we developed a geospatial web-based integrative WEF nexus tool, called the iWEF, to enhance the analytical tool developed by Mabhaudhi *et al.* (2019) and Nhamo *et al.* (2020a,b). As a digital and web-based tool, the iWEF is meant to improve the operational time of the existing Excel-based WEF nexus integrative model. Therefore, the study provides a user-friendly digital WEF nexus tool (the iWEF) that improves the operational time and cost of the existing integrative analytical model.

3.2 Materials and Methods

The iWEF tool was developed using model building, programming and web development tools, and integrating a GIS module that facilitates geospatial analytic capabilities by providing quantitative and qualitative spatial information about the WEF nexus. This section provides the background information on the integrative WEF nexus analytical model and the stepwise model development.

3.2.1 Description of the WEF nexus integrative analytical model

The integrative WEF nexus analytical model was developed by Mabhaudhi *et al.* (2019) and Nhamo *et al.* (2020a) as a spreadsheet based on the Analytic Hierarchy Process (AHP). The model establishes quantitative relationships among WEF resources. Its main strength is the capability to indicate resource utilisation and performance over time and inform policy and decision-making on priority areas for immediate intervention. The key feature of the tool is, therefore, its capability to provide a holistic assessment of synergies and trade-offs to improve the management, efficiency, and productivity of resources for sustainable development (Nhamo *et al.*, 2020a). The model computes composite indices using WEF nexus sustainability indicators, including water availability, water productivity, energy accessibility, energy productivity, food self-sufficiency and cereal productivity (Figure 3.1).

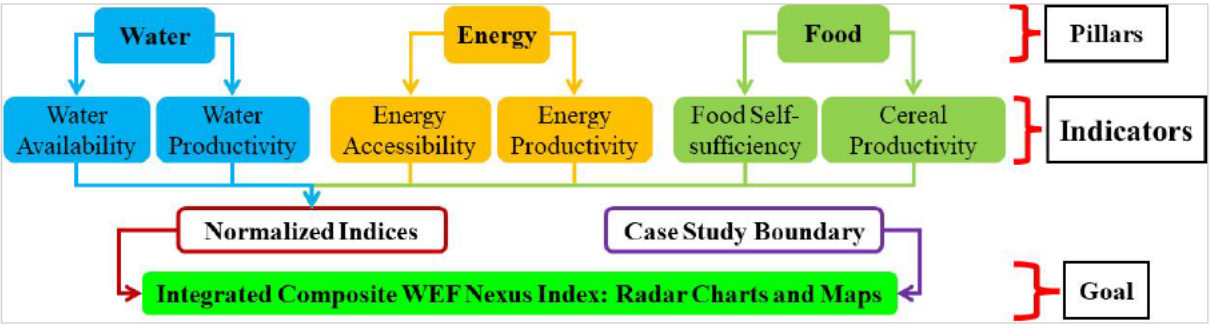


Figure 3.1: Pillars, indicators, and goal in the conceptual framework for iWEF model development

These six indicators are compared against each other in a pairwise comparison matrix (PCM) based on the hierarchy established through the Saaty process and scale (Appendix C), and sometimes supported by, if available, expert opinion, literature, or recognized databases (e.g.,

national statistics, World Bank, Aquastat). All indicators and their characteristics (definitions and polarity) were adopted as in Nhamo *et al.* (2020a), except for energy productivity (EP) and food self-sufficiency (FSF) to maintain consistency in polarity whereby higher values are desirable across all six indicators. While energy productivity was synonymous with energy intensity which was defined as the energy supplied to the economy per unit value of economic output (MJ/GDP) in Nhamo *et al.* (2020a), energy productivity (EP) is the economic benefit derived from each unit of energy used ($GDP/MJ) in the current version of the iWEF model (ASE and GAEP, 2016). Similarly, while food self-sufficiency was referenced to prevalence of moderate or severe food insecurity in the population (%) in Nhamo *et al.* (2020a), the current version of the iWEF model uses FSF as the proportion of the total population who have sufficient food during the reference year.

3.2.2 The conceptual model for the iWEF modelling tool

The iWEF model (Figure 3.1) is based on the AHP, a multi-criteria decision-making (MCDM) approach, which is composed of indicators and their pillars as already alluded to. The conceptual model (Figure 3.2) highlights the flow of data for the iWEF tool between the four major sub-modules which form the model: the database, user interface, computations and results (Figure 3.2).

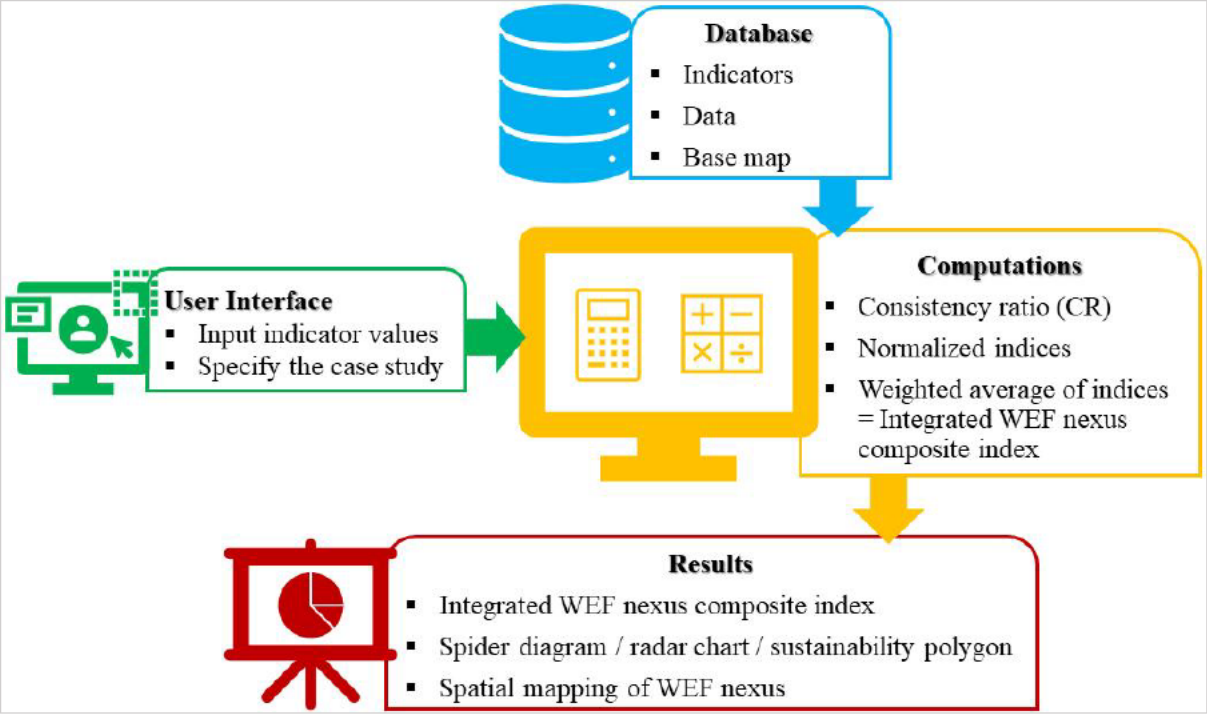


Figure 3.2: The mode of operation for iWEF using the modelling tool's sub-modules

The four modules indicated in Figure 3.2 are established in such a way that they work harmoniously to facilitate the tool to produce the desired results. Generally, the graphic user interface (GUI) facilitates users to interact with the tool's database and specify the WEF resources input data from the indicators. The analysis module converts the data from the indicators into useful quantitative relationships which can be displayed in the form of tables, graphs, and maps for easy interpretation. The iWEF model automatically determines the consistency of a provided input pairwise comparison matrix (PCM) and either accepts if the consistency ratio (CR) value is less than 0.1 (or 10%) or rejects it if the CR value is above 0.1 (Saaty and Vargas, 2012). A key feature in the iWEF model is the comparison and visualization of results for several case studies using spider diagrams (or radar chart or sustainability polygon) and WEF nexus maps plotted on the same axes and scale.

3.2.3 Mathematical (quantitative) model for iWEF

3.2.3.1 Determining the consistency of the pairwise comparison matrix (PCM)

Like the Excel-based tool (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a), the iWEF integrates the indicators (Brunelli, 2015) by normalising WEF indicators data to establish composite indices. The composite indices are then used to calculate the weighted average, which is then considered as the integrated WEF nexus composite index. According to Saaty (1987), the AHP is a measurement theory for deriving ratio scales from discrete and continuous paired comparisons to set priorities and make the best decisions. The AHP comparison matrix is determined by comparing two indicators simultaneously using Saaty's scale (Appendix C), which ranges between one and nine (Saaty, 1987), as indicated in the iWEF user manual (Taguta *et al.*, 2022b).

Based on the AHP method, the iWEF model computes the consistency ratio (*CR*), which measures the randomness and consistency of the pairwise judgements from the ratio of the consistency index to the randomness index. The *CR* value is calculated as in Mu and Pereyra-Rojas (2017) as a function of the consistency index (*CI*), and the random consistency index (*RI*) which depends on the order *n* of the matrix (Saaty and Vargas, 2012) (Appendix D). *CI* depends on the principal or maximum eigenvalue which is estimated by Teknomo (2006), Bunruamkaew (2012), and Mu and Pereyra-Rojas (2017) (Appendix D). According to Saaty and Vargas (2012), a CR value of less than 0.1 or 10% is acceptable for the CR. A higher value (CR > 0.1 or 10%) is unacceptable due to implied inconsistency in the pairwise comparison judgements (Appendix D) (Saaty and Vargas, 2012).

3.2.3.2 Calculation and normalisation of indices by AHP-MCDM technique (Appendix D)

The AHP calculates the indices from indicators by taking the eigenvector corresponding to the largest eigenvalue of the matrix and then normalising the sum of the components (Appendix D) (Saaty, 1990; Saaty and Vargas, 2012). The overall importance of each indicator is then determined as a normalised index (Appendix D) (Nhamo *et al.*, 2020a). The iWEF model, therefore, determines the integrated WEF nexus composite index as a weighted average of the six normalised indices, where the weights are the integers one to six of which the highest weight

(6) is assigned to the largest normalised index and the lowest weight (1) is assigned to the smallest normalised index (1). Thus, the values of the integrated WEF nexus composite index in this case range from 0.048 (low) to 0.286 and can be interpreted on its level or class of sustainability (Table 3.1; Appendix D) (Nhamo *et al.*, 2020a).

Table 3.1: WEF nexus indices performance classification categories (Nhamo *et al.*, 2020a)

Index/indicator and units	**Category and interpretation**			
	Unsustainable	**Marginally sustainable**	**Moderately sustainable**	**Highly sustainable**
Integrated WEF nexus composite index (i)	$0.048 \leq i < 0.107$	$0.108 \leq i < 0.167$	$0.168 \leq i < 0.226$	$0.227 \leq i \leq 0.286$
Water availability (m^3/per capita)	< 1 700	1 700 ≤ x ≤ 6 000	6 000 < x ≤ 15 000	> 15 000
Water productivity (US$GDP/$m^3$)	< 10	10 ≤ x ≤ 20	20 < x ≤ 100	> 100
Energy accessibility (% of population)	< 20	20 ≤ x ≤ 50	50 < x < 90	90 ≤ x ≤ 100
Energy productivity ($GDP/MJ)	< 0.11	0.11 ≤ x < 0.2	0.2 ≤ x ≤ 0.33	> 0.33
Food self-sufficiency (% of population)	< 70	70 ≤ x ≤ 85	85 < x ≤ 95	> 95
Crop productivity (kg/ha)	< 500	500 < x ≤ 2 000	2 000 < x ≤ 4 000	> 4 000

The value of the integrated WEF nexus composite index represents the overall performance of resource development, utilisation, and management (Nhamo *et al.*, 2020a). Similarly, indices performance classification categories for the six indicators were adopted from Nhamo *et al.* (2020a), except for energy productivity and food self-sufficiency (Table 3.1). The sustainability category scale for these two indicators (energy productivity and food self-sufficiency) changed in values and polarity from the ones provided in Nhamo *et al.* (2020a).

3.2.4 Development of the web-based and GIS-linked iWEF tool

The development life cycle for the iWEF modelling tool was an adaptation of the Environmental Protection Agency (US-EPA) modelling life cycle (EPA, 2009) and the Modified Waterfall model (Conrad *et al.*, 2016), which allows developers to return to a previous phase ideally confined to connecting steps. The development of the iWEF application followed this non-linear and bottom-up development life cycle which offered the possibility and flexibility of iterating to the previous stage(s) for correction, verification, validation and improvement. This development life cycle was also useful for keeping the web application development project's progress in order, straightforward, simple, and easy to understand. The development life cycle provides essential feedback that is critical for making informed decisions.

The iWEF tool and its modules were developed with programming, web framework and visualization tools, including Python, Django, PostgreSQL, Visual Studio Code, Git, JavaScript and Dash-Plotly. The GIS module was integrated into iWEF through Leaflet, an open-source JavaScript library for building web mapping applications using an OpenStreetMap as a base map. The Visual Studio Code editor was used for writing codes, while GitHub was used for version control, backup and spinning the server to test the application before public deployment. The web-based and GIS-enabled iWEF model was developed with two common tasks: the back-end and the front-end.

3.2.4.1 The iWEF back-end

The back end comprises Django, a Python framework for web development, and Dash-Plotly, a Python framework for data visualization. GeoDjango, a Django module, was used to extend Django's capability to store and work with geographic/spatial data. The database technologies included the PostgreSQL database management system. PostgreSQL and its spatial extender, PostGIS, which adds spatial functionalities, are both Open Geospatial Consortium (OGC) Web Map Services standards compliant. PostGIS allows PostgreSQL to augment support for geographic objects, thus understanding coordinate systems, projections and transformations (MacEachren *et al.*, 2008). The model’s computation component consists of the codes and algorithms from governing equations for reciprocity of indicator values, calculating CR values,

sums, weights, indices of indicators, and the overall index (integrated WEF nexus composite index) as the weighted average. Dash-Plotly was used for creating graphs and maps of the iWEF model outputs.

3.2.4.2 The iWEF front-end

The HyperText Markup Language (HTML) markup language, Cascading Style Sheets (CSS) language, and JavaScript programming language were used for developing the front-end (including the user interface). The languages proved efficient in the interaction between the user and the system. The Balsamiq Wireframes software was used to draw the wireframes of iWEF. The front-end components and functions are explained in detail in the iWEF user manual (Taguta *et al.*, 2022b). The final outputs include a weighted average index (the integrated WEF nexus composite nexus), a spider diagram showing WEF trade-offs and synergies (Flammini *et al.*, 2014; FAO, 2021), and maps showing the spatial variation of the WEF nexus. The spider graph and its shape illustrate and compare sectors' performance regarding sustainable or unsustainable management (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a,b).

3.2.4.3 Coupling GIS and iWEF model

GIS can be coupled to WEF tools in various ways, including 'soft-linked' and 'hard-linked' integration (Eldrandaly, 2007). The major difference between soft-linked and hard-linked integration of WEF nexus tools and GIS is the manual and automated exchange of information, respectively (Figure 3.3).

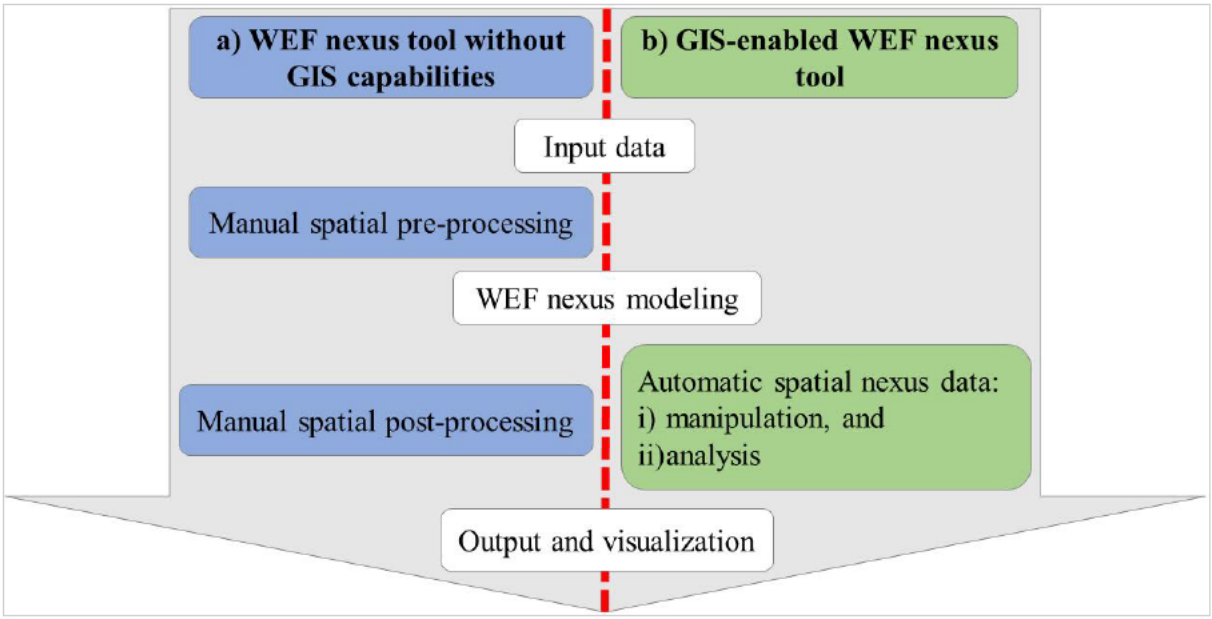


Figure 3.3: Differences in WEF nexus spatial analysis using a typical (a) left side – WEF nexus tool that uses soft-linked integration with GIS, and (b) right side – GIS-enabled hard-linked WEF nexus tool (Adapted from Burger, 2018; Burger and Abraham, 2020)

The iWEF model was integrated into GIS by hard-linking to an open-source base map so that users can locate their case studies, and spatially analyse and visualize their results. Hard-linking was chosen over soft-linking because hard-linked integration is automatic, simple and user-friendly in exchanging input/output information between the WEF nexus tool and GIS. The base maps commonly used in web-based applications include those available in ArcGIS Online, Google Maps, OpenGIS and OpenStreetMap. Base maps are used as foundation layers to support a range of web maps or web mapping applications. Using open-source base maps reduces the overall cost and time of developing and implementing the GIS-enabled WEF nexus model. The iWEF model was geospatially enabled through a 'hard-linked' GIS integration of the WEF nexus model with open-source base maps displayed on the front-end using the JavaScript library, Leaflet. The leaflet can be used with several plugins that provide open-source base maps. Dash-Plotly allows users to choose different study areas under study, interactively, and display and contrast WEF nexus results.

3.2.4.4 Online deployment and dissemination of the iWEF modelling tool

The iWEF modelling tool (Taguta *et al.*, 2022a) was deployed on the internet on a dedicated website (https://www.iwef.app/) with a Secure Sockets Layer after considering pertinent factors such as costs and the security and privacy of the tool and its users. To promote its

applicability by prospective users, the iWEF modelling tool is accessible freely as an open-source web application. Dedicated accounts and channels were created for the iWEF model to facilitate its dissemination to interested users in wide audiences on online media and communication platforms such as LinkedIn, SlideShare, Facebook, YouTube, Twitter, Instagram, and Scribd.

3.2.4.5 Operating procedure and key outputs for the iWEF modelling tool

To operate iWEF, users must chronologically follow the steps presented in Figure 3.4. Before modelling in iWEF the user (i) identifies the spatial boundaries for their case study, and (ii) engages experts and stakeholders to collect and prepare input data for the iWEF model through pairwise comparison of indicators using a scale from 1/9 (the lowest and most insignificant relationship) through 1 (equal importance) to 9 (the highest and most significant relationship).

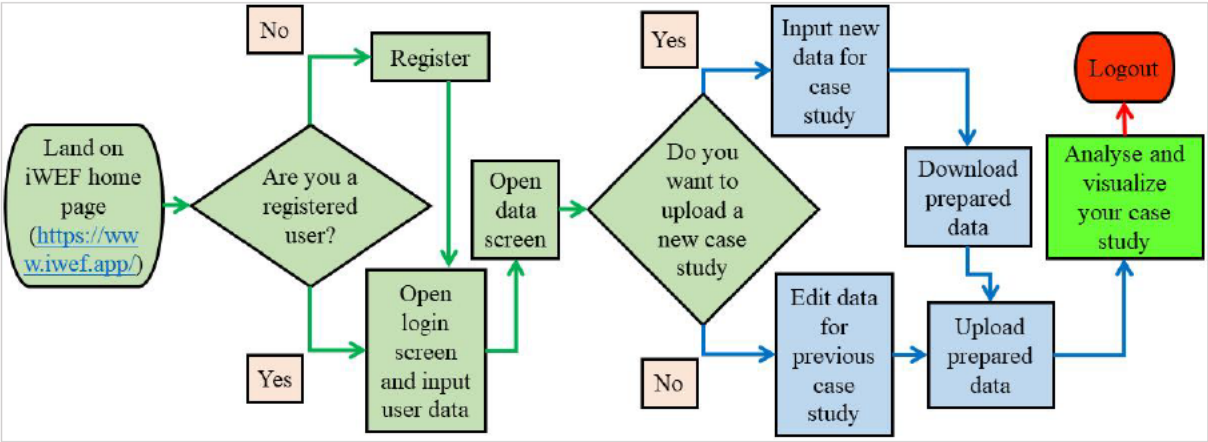


Figure 3.4: The user flowchart for the iWEF modelling tool

The key inputs for the iWEF model are pairwise comparison matrices (PCMs) developed from stakeholders' pairwise judgments of the six indicators based on the hierarchy established through the Saaty process and scale (Appendix C), and sometimes supported by, if available, expert opinion, literature, or recognized databases (e.g., national statistics, World Bank, Aquastat). The target stakeholders depend on the scale and level of analysis and modeling in iWEF also requires delineating the case study boundaries in the application. The key outputs in the iWEF model are quantitative, graphical and spatial (Table 3.2).

Table 3.2: Outputs in the iWEF model

iWEF outputs	**Description / Interpretation**
Pairwise comparison matrices (PCMs)	Initial, iterated and final
Consistency ratio(s)	Initial, iterated and final
Normalised indices	Relative performance of indicators (higher value = higher performance)
	Entry points for interventions
	Likely cross-sectoral impacts of interventions
Integrated WEF nexus composite index(es)	Level of sustainability of management of WEF resources from an integrated nexus perspective (higher value = higher performance)
Radar chart (spider diagram or sustainability polygon)	Shape: Regular / circular = balanced management. Irregular shape of centrepiece = unbalanced and biased management of WEF resources
Spatial map(s)	Comparison of case studies
Quantitative values of indicators	Support interpretation of the iWEF results

The spider diagrams (or radar charts or sustainability polygons) display normalized indices of relative performance and interrelationships between WEF sectors (Table 3.2). A deformed amoeba shape is symptomatic of an unbalanced WEF system, while a circular shape signifies balanced management of WEF resources. The maps show the location of the case study and spatially visualize the integrated WEF nexus composite index as a measure of WEF nexus performance. The lower value (close to 0.048) of the integrated WEF nexus composite index, the more unsustainable the WEF resource management is, while a higher value (closer to 0.286) signifies highly sustainable WEF resource management (Table 3.1). The same applies to indices of performance of the sectoral indicators. In the iWEF model, the farther away from the centre an indicator is plotted in the radar chart, the higher and desirable its relative performance. If available, the values of and sustainability classification categories for the six as presented in Table 1 are used for interpreting and reporting the relative performances of the sectors and indicators, as well as proposing potential WEF nexus solutions for improving the sustainability of the case study.

3.2.5 Testing and trial runs for the iWEF modelling tool

The iWEF tool was tested to ascertain its compatibility with common browsers and devices, on top of accuracy and reliability in computing the CR value and the integrated WEF nexus composite index. The iWEF modelling tool was tested for loading and execution in common web browsers. The modelling tool was also tested for compatibility with common electronic devices. Two pairwise comparison matrix datasets were randomly generated (Appendix E) to test the accuracy of the iWEF modelling in calculating the CR value; (i) within an acceptable range of less than 0.1 (or 10%), and (ii) at unacceptable values of 0.1 (or 10%) and above (Teknomo, 2006; Bunruamkaew, 2012; Mu and Pereyra-Rojas, 2017). The two different PCMs were run in the iWEF modelling tool, and the results were compared with those from the simple web-based AHP Priority Calculator (AHP Online System – AHP-OS) by Goepel (2022).

The initial version of the geospatial web-based integrative analytical tool for the water-energy-food nexus was tested with input PCM data from three case studies that previously applied iWEF's predecessor, i.e., the spreadsheet-based tool (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a,b). The iWEF input data including the PCMs for the three case studies are provided in the relevant publications (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b). The results were visually and quantitatively compared with those from the original case studies in which the spreadsheet-based tool was previously used (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b). All three case studies were run and analysed simultaneously in iWEF to test the modelling tool's ability to plan and analyse WEF nexus scenarios.

3.3 Results and Discussion

3.3.1 Browser and device compatibility and screen resolutions

The iWEF modelling tool was successfully loaded and executed in Microsoft Edge (v99.0.1150.36), Google Chrome (v99.0.4844.51) and Mozilla Firefox (97.0.1). The modelling tool was also successfully loaded and executed on laptops, desktop computers, smartphones, and tablets at good resolutions. This shows that the iWEF modelling tool is compatible with common web browsers and electronic devices. However, some users have complained inability

to interact with the iWEF tool on devices based on the Mac operating system (macOS by Apple).

3.3.2 Calibration of iWEF modelling tool for CR value

The results from running inconsistent and consistent pairwise matrix (PCM) data sets in the iWEF modelling tool to test its accuracy and reliability in determining the consistency and randomness of input data are presented in Appendix E. Similar to the AHP Priority Calculator (AHP Online System – AHP-OS) by Goepel (2022) and the offline tool (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b), iWEF was able to reproduce CR values of 0.31 for the inconsistent dataset and 0.07 for the consistent dataset. This shows that the iWEF modelling tool is accurate and reliable in determining the CR value. Thus, the iWEF modelling tool can reliably inform and guide users in ensuring the randomness and consistency of their pairwise comparison matrix judgements. This is crucial in the sound determination of integrated WEF nexus indices that represent WEF interconnections in their case studies.

3.3.3 Validation of iWEF tool with data and findings from previous case studies

The integrated WEF nexus composite index (0.200) from the iWEF modelling tool and its predecessor were similar to the southern Africa regional case study by Mabhaudhi *et al.* (2019) for 2017, as illustrated in Figure 3.5.

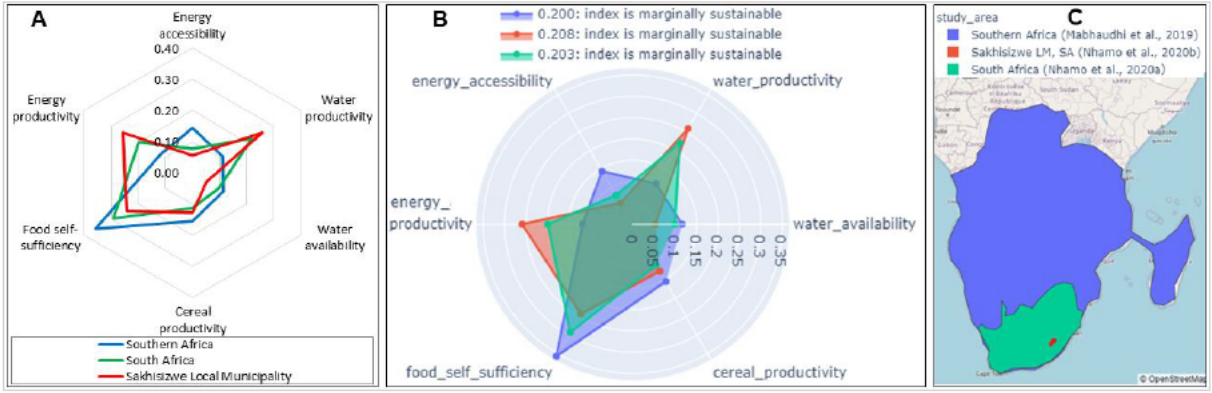


Figure 3.5: Multiple case study WEF nexus analysis results at regional (southern Africa), local municipal (Sakhisizwe), and national (South Africa) scales (a) quantitatively using the spreadsheet-based tool (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b), (b) quantitatively using the iWEF modelling tool, and (c) spatially using the iWEF modelling tool

The value-add of the iWEF tool is that it provides a spatial component (Figure 3.5c) to the analysis. The iWEF modelling tool, therefore, offers the extra benefit of locating the case study area and spatially mapping and visualizing the WEF nexus (Figure 3.5c), features that are absent in the original spreadsheet-based tool. Therefore, the tool provides an extra spatiotemporal analysis of the integrated management of the interlinked resources. Detailed analysis and interpretation of the normalised indices and the integrated WEF nexus composite indices are available in Mabhaudhi *et al.* (2019). The results show that managing the WEF nexus is moderately sustainable the southern Africa region.

For the South African national case study by Nhamo *et al.* (2020a) for 2015, the iWEF modelling tool reproduced the quantitative (integrated WEF nexus composite index = 0.203), visual and graphical results similar to the spreadsheet-based tool (Figure 3.5). Additionally, the iWEF modelling tool spatially characterised the WEF nexus (Figure 3.5c), a characteristic absent in the original spreadsheet-based tool. Detailed analysis and interpretation of the normalised indices and the integrated WEF nexus composite index are available in Nhamo *et al.* (2020a). The management of the WEF nexus in South Africa is moderately sustainable, with room for improving citizens' access to energy, water availability and cereals' productivity.

The iWEF modelling tool produced results (integrated WEF nexus composite index = 0.208; the similar shape of radar chart) similar to the original spreadsheet-based tool for the local scale Sakhisizwe Local Municipality (South Africa) case study using 2018 data by Nhamo *et al.* (2020b), as shown in Figure 3.5. Unlike the spreadsheet-based tool, the iWEF modelling tool managed to spatially map and visualize the WEF nexus (Figure 3.5c). Detailed analysis and interpretation of the normalised indices and the integrated WEF nexus composite index are available in Nhamo *et al.* (2020b). At this local scale, management of the WEF resources is moderately sustainable. The municipality needs to explore nexus-relevant interventions that improve water availability, energy accessibility and cereal productivity.

The iWEF modelling tool was also able to simultaneously analyse and quantitatively and spatially visualize the WEF nexus for multiple (three) but individual case studies across scales on the same axis and map background, as shown in Figure 3.5. This is testimony that the iWEF tool is applicable at different spatio-temporal scales. Simultaneous visualization of results from multiple case studies at different spatio-temporal scales in the iWEF tool allows users to develop, analyse and compare different states of the WEF nexus for different time slices or locations, a key feature in analysing and planning WEF nexus scenarios. For example, as

illustrated in Figure 3.5, the potential exists to use the current version of the iWEF modelling tool to explore how WEF systems will likely unfold with time, testing possible adaptation and their impacts, which can aid in planning for sustainable and balanced development.

From the testing, verification and validation instances, the geospatial web-based iWEF tool is trustworthy in computing and presenting the WEF nexus at multiple scales. It automatically checks the consistency and randomness of pairwise comparison judgements and thus informs users on the quality of their input data. The tool visualizes outputs quantitatively, graphically and spatially for users to identify and appreciate cross-sectoral linkages and performances. The iWEF modelling tool can confidently be used in other case study areas of interest to characterise the WEF nexus and identify areas that need intervention for implementing the WEF nexus approach. The tool is valuable in the day-to-day operations of policy- and decision-makers to bring together water, energy and agriculture sectors. It provides informed policy and investment decisions by indicating priority areas for strategic intervention, closing the gap between the WEF nexus theory and actual practice.

3.3.4 Limitations of the iWEF model (version 1.0)

The current version of the iWEF model is fixed by its operating principle (AHP) to only six indicators. Work is needed to extend the number of indicators in the iWEF model, which is currently limited to a maximum of nine indicators as restricted by the AHP MCDM technique. Alternatively, the operating principle for the iWEF model may be changed from AHP to another MCDM technique that can accommodate more than nine indicators or criteria such as fuzzy AHP. In the same vein, there is a need to make customisable the naming and number of indicators for flexibility and adaptability according to user needs and context. The iWEF 1.0 can advise the consistency of PCM judgements, however, future efforts will be made for the tool to pinpoint the outlier judgements so that they can be systematically reconsidered with relative ease. As the current version is only available online, future efforts need to develop a desktop version and open-source codes, with the latter format promoting transparency and opportunities for improvement, customisation and integration. The current version of the iWEF tool is compatible with operating systems such as Windows (Microsoft) and Android, but not others such as Mac operating system (macOS by Apple).

3.4 Conclusions and Recommendations

This study introduced a user-friendly, freely accessible, geospatial web-based integrative WEF nexus analytical modelling tool, the iWEF with open-source base maps. The web-based version is a freely available, easy-to-use and open-source tool. Users have a ready-made tool to accurately determine the CR values, the normalised indices and the integrated WEF nexus composite indices, with an additional ability to spatially map and visualize the WEF nexus relationships. The current version of the tool is descriptive, indicative, and diagnostic, and thus requires further enhancing its abilities towards being prescriptive and predictive for WEF nexus scenario planning. Further studies should include the development of (i) iWEF plugins for off-the-shelf free and commercial GIS software such as ArcGIS and QGIS, and (ii) desktop PC and Android application versions of the iWEF modelling tool that can work offline for compatibility and convenience with various users and devices. A need exists to enhance the compatibility of the current version of iWEF tool with Mac operating system (macOS) for relevant users and devices. Other recommended improvements for the iWEF modelling tool include (i) increasing the number of criteria (i.e., indicators), (ii) making it adequately flexible such that users can specify their WEF sectors/dimensions and indicators according to context, and (iii) developing sub-modules for WEF nexus scenario planning.

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4 THE STATE OF THE WATER-ENERGY-FOOD NEXUS AT SUB-NATIONAL SCALES: THE CASE OF SOUTH AFRICA

Abstract

Despite South Africa's commitment to universal access to water, energy and food (WEF), it continues to suffer from WEF insecurities. Addressing the status quo requires reflecting, rethinking, and shifting from the "business-as-usual" management of WEF resources. South Africa embraced the water-energy-food (WEF) nexus approach, including in its policy and research agenda. This study sought to assess the state of the WEF nexus in Inkomati-Usuthu Water Management Area (IUWMA) and Ehlanzeni District Municipality (Ehlanzeni DM) in South Africa, using mixed methods including observations, literature, stakeholder engagement, and modelling. The key inputs were pairwise comparison matrices (PCMs) development from key WEF-related expert stakeholders' pairwise judgements of the six iWEF model indicators based on the hierarchy established through the Saaty process and scale. Since the state of the WEF nexus is an outcome of implementation of the WEF nexus approach, the former can serve as empirical evidence and proxy indicator for the latter. IUWMA and Ehlanzeni DM have iWEF (geospatial web-based integrative water-energy-food nexus analytical modelling tool) integrated WEF nexus composite indices of, respectively, 0.209 and 0.210, out of a possible 0.286 maximum. This indicates that the management of WEF resources in IUWMA and Ehlanzeni DM is moderately sustainable, with an overall unbalanced management of WEF resources. As initially hypothesised, the performance of almost all the six WEF security indicators is moderately sustainable in both case studies, and prioritised interventions are needed to improve resource security in the water sector significantly, starting with water availability and water productivity. Prioritised interventions such as dam construction, renewable energy, removal of alien vegetation, solar water heaters, groundwater use, waste-to-energy and WEF systems co-location can potentially improve WEF security for all in IUWMA and Ehlanzeni DM. However, these interventions should be planned and implemented from a nexus perspective to optimise synergies and minimise trade-offs and risks. With the IUWMA catchment already overallocated, opportunities for improving WEF security lies in management of available resources from a nexus perspective. Mining is a key nexus node that provides fuel for energy production and economic development but competes with other sectors for water and land whose quantity and quality it compromises. Similarly, climate and

climate change through its observed and projected impacts is a key determinant of the WEF nexus in IUWMA and Ehlanzeni DM. To conclude, southern African countries share somehow similar history, context, and WEF-related developmental challenges and it can be inferred that their sub-national scales have moderately sustainable states of the WEF nexus which require nexus planning of integrated contextualised solutions for improving collective WEF security for all.

Keywords: global South, sub-national scale, iWEF, WEF nexus model, nexus, resource security, SDG, South Africa

4.1 Introduction

Water, energy and food (WEF) resources, together with land, are fundamentals for socio-ecological integrity and dignity, economic prosperity, livelihoods, and sustainable development (Amer *et al.*, 2017; Leal Filho *et al.*, 2018). The Government of South Africa is committed to WEF resources for all through its Constitution (GoSA, 1996) and policy framework including the National Development Plan 2030 (NDP2030, 2012; DWS, 2018). However, the continued depletion and degradation of WEF and land resources amidst climate change threaten humankind's ability to safeguard WEF resources security for all and achieve the Sustainable Development Goals (SDGs) (FAO, 2017; Sachs *et al.*, 2023). According to the latest reports, South Africa has an SDG index of 64% (ranked 110th out of 166 on the global list), which is retrogressing and below the global average of 66.7% (Sachs *et al.*, 2023). The same can be said for the achievement of individual SDGs which continue to face challenges, including SDG#6 (clean water and sanitation), SDG#2 (zero hunger) and SDG#7 (affordable and clean energy) (Sachs *et al.*, 2023).

In 2021, like in 2008, 88.7% of South African households had access to piped or tap water in their dwellings, showing a gradual decline from a high of 90.9% in 2012. In the same year, 89.3% (a 0.7% decrease from 2020) of South African households were connected to the mains electricity supply, while 7.7 - 10% cooked with unclean energy sources, including wood (Stats SA, 2022a). Despite the gradual increase with some stagnation in recorded number of households connected to the mains electricity supply, the reliability of electricity supply is low due to the demand growing faster than the insufficient generation, which is causing frequent and worsening electricity load shedding (manual load reduction) from 2007-2008 (GoSA, 2022b; Eskom, 2023a; The Outlier and Eskom Se Push, 2023). During 2022/23, 21 - 24% of

the South African population were reportedly food insecure in South Africa, and this was higher than the 5-year average (2017-2021) and the previous year (2021/22) (SADC, 2022; Stats SA, 2022a; GAFS, 2023). With only six years left to finish the 15-year 2030 Agenda for Sustainable Development (UNGA, 2015), preliminary evidence of progress from 2015 to date shows that South Africa is yet to fulfil its promises of WEF security for all (DWAF, 1994; GoSA, 2002; NPC, 2012; DWS, 2021) and may fail to achieve universal and equitable access to water, energy and food (Sachs *et al.*, 2023). However, these WEF resource security statistics are national values aggregating urban and rural areas, and the latter in the southern Africa region have always lagged the former in economic development, provision of basic services, and access to resources. Thus, WEF insecurity is worse in rural areas (Mabhaudhi *et al.*, 2019).

A key determinant of WEF resources security is how they are planned, developed and managed to meet normal demand or deal with scarcity. Strategic resources such as water, energy and food are inextricably and concomitantly linked in a water-energy-food (WEF) nexus such that actions in one sector influence the other sectors, either synergistically or adversely in the hydrological, biological, social, and technological realms (Hoff, 2011; Beekma *et al.*, 2021). However, WEF resource planning and management remains sectoral in South Africa, just like in many other countries. Linear and sectoral approaches in resource management have outlived their usefulness, reached their limits and caused mismatches in prioritisation and decision-making, which hinders sustainable development (Nepfumbada, 2020; DWS, 2022b). According to the Southern African Development Community (SADC) and the Government of South Africa, conventional fragmented, silo-based and incoherent development approaches undermine cost-effective implementation of programmes and projects and cause duplication, thus leading to sub-optimal delivery of services and failure to address the triple challenges of poverty, inequality and employment (SADC, 2016; COGTA, 2020a; EDM, 2021). Similarly, the lack of integrated planning between national departments, provincial entities, local government, and key stakeholders undermines the effective management of resources for transformation, equity, efficiency and sustainability (DAFF, 2015; IUCMA, 2019; IUCMA, 2020). Planning WEF systems in conventional and traditional "business as usual" silos and sectors perpetuates and amplifies WEF resource use competition, inefficiency, and insecurity and is no longer an option if society is to secure WEF resources for all today and in the future (FAO, 2017; Smith *et al.*, 2023). Thus, there is a need to think outside and beyond sectoral boxes and silos for better and sustainable development, utilization and management of resources. As such, the WEF nexus approach seeks to understand the interconnections between

WEF resources, optimize the synergies, minimise the trade-offs, and harmonize actions to enhance resource security for economically efficient, socially equitable and environmentally sustainable development (Mpandeli *et al.*, 2018; Naidoo *et al.*, 2021).

Comprehensive assessment for informing WEF nexus policy and practice needs to ideally integrate qualitative data, quantification by analytic tools, stakeholder engagement, real-life observations, and exploring plausible alternative WEF nexus scenarios. Such integrated approaches facilitate navigating complexities, capturing uncertainties, better understanding linkages, and developing WEF systems through the WEF nexus approach (Beekma *et al.*, 2021; Schipper *et al.*, 2022). South Africa has witnessed significant WEF nexus work at multiple scales, including policy dialogues (GWP-SA, 2022) and research (Mabhaudhi *et al.*, 2019; Simpson *et al.*, 2019; Nhamo *et al.*, 2020a,b). Despite the importance of hydrologic and sub-national boundaries in resource allocation, management, and service delivery, only one case study focused on a catchment (Dlamini *et al.*, 2023a; Dlamini *et al.*, 2023b), a local municipality (Nhamo *et al.*, 2020b), and none for district municipalities, the latter which is the theatre of South Africa's integrated district-based District Development Model (DDM) (COGTA, 2020a).

South Africa acknowledges the value of integrated planning and embraced the WEF nexus concept in various spaces including research (e.g., the Water Research Commission (WRC)'s WEF Nexus Lighthouse), technical and policy levels (regional policy dialogues) (Radebe-Tsotetsi, 2017; WRC, 2017; DWS, 2024). Some elements of the South Africa's sectoral policy framework consider the WEF nexus approach as a key principle for guiding development and implementation of Just Transition (NPC, 2019), water conservation/water demand management (DWS, 2021), the National Water Security Framework (Nepfumbada, 2020), and the Irrigation Strategy for South Africa (DAFF, 2015). This study's research problem is the paucity of evidence of the WEF nexus that can inform implementation of the approach at sub-national scales in southern Africa, including South Africa where the WEF nexus approach has been successfully embedded in some sectoral policies (Nhamo *et al.*, 2020a; Naidoo *et al.*, 2021; Taguta *et al.*, 2022). This research aimed to assess the state of the WEF nexus as a proxy of the status of implementation of the WEF nexus approach in South Africa using a case study approach at sub-national scales, particularly at the water management area and district municipality level. It is hypothesised that, from a nexus perspective, the management of WEF resources is moderately sustainable and there is a need for interventions that can improve the status quo in the two sub-national case studies. The research is envisaged to provide evidence

on the sustainability of the management of WEF resources from a nexus perspective, highlighting priority areas for intervention in IUWMA and Ehlanzeni DM.

4.2 Materials and Methods

To assess the state of the WEF nexus in Inkomati-Usuthu Water Management Area (IUWMA, henceforth) and Ehlanzeni District Municipality (Ehlanzeni DM, henceforth) in South Africa, this study applied mixed methods, specifically integrated WEF nexus modelling (the geospatial web-based integrative water-energy-food nexus analytical modelling tool, iWEF) with inputs from key expert stakeholders, as well as observations, databases, and literature (Figure 4.1). The iWEF model was initially developed as a spreadsheet by Nhamo *et al.* (2020a) and further enhanced into an open access geospatial web-based tool by Taguta *et al.* (2023). It is reasonably assumed that the state of the WEF nexus is determined by the status of implementation of the approach, thus the former is a representative proxy and reflection of the latter.

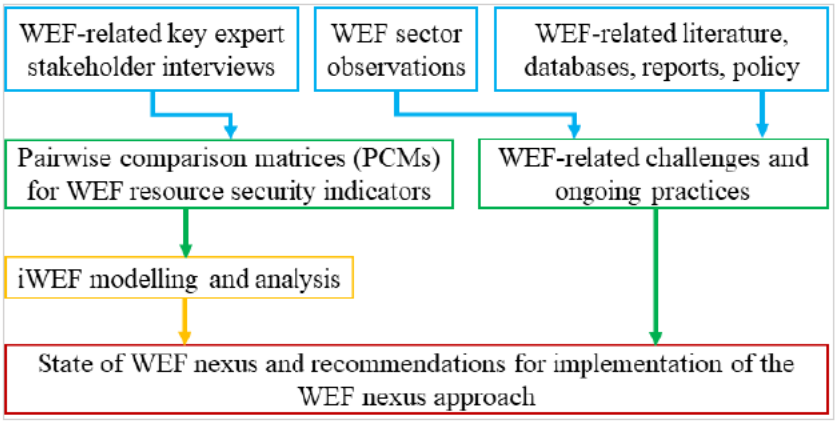


Figure 4.1: Study flowchart

A water management area (WMA) is a regional or catchment area managed by a catchment management agency (CMA) in South Africa (DWS, 2023). For example, the Inkomati-Usuthu Catchment Management Agency (IUCMA) is the water resource management authority mandated with water resource management functions within IUWMA (IUCMA, 2023a,b). The three-tier system of government in South Africa consists of national, provincial and local levels, the latter which includes metropolitan (category A), district (category C) and local (category B) municipalities (GCIS, 2021). A district municipality has municipal executive and legislative authority in an area with more than one local municipality while a local municipality

shares its municipal executive and legislative authority with its host district municipality. The WEF-related mandate of a district municipality within its area of jurisdiction is integrated sustainable and equitable social and economic development including integrated development planning and promoting bulk infrastructural development and services such as for potable water supply, bulk supply of electricity, disposal of waste (domestic, sewage and solid), and establishment, conduct and control of fresh produce markets and abattoirs. A district municipality is also responsible for building the capacity of and promoting equitable distribution of resources between its enclosed local municipalities (GoSA, 1998).

Local governments such as district municipalities are at the forefront of ensuring and providing universal access to safe water and sanitation, reliable and clean energy, and adequate and nutritious food (Sachs *et al.*, 2023). The National Climate Change Response White Paper (2011) and National Water Resource Strategy 3 (Draft 2.6) for South Africa require implementing the best water management practices at local, regional or catchment level, in defined water management areas for water security and resource protection in the changing climate (GoSA, 2011; DWS, 2021). Although these management units are mainly water-centric hydrological boundaries, they are valuable WEF nexus units in which the water sector provides water to other strategic sectors such as agriculture and energy, absorbs return flows from the use sectors, and contributes to instream environmental roles (Ringler *et al.*, 2018).

4.2.1 Case study areas

Both IUWMA and Ehlanzeni DM are located in Mpumalanga province (South Africa) which is witnessing several interconnected challenges and developments including energy generation, decommissioning of coal-fired power stations, irrigated agriculture and competition for land between agriculture, mining (especially coal for energy generation) and industrial or residential use in an environment of water stress due to overallocation, groundwater depletion and climate change, among others (WRC, 2017; Simpson *et al.*, 2019; IUCMA, 2023a).

4.2.1.1 Inkomati-Usuthu Water Management Area (IUWMA)

IUWMA (approximately 36256 km^2) in Mpumalanga Province is one of the nine water management areas (WMAs) in South Africa, situated in the north-eastern part of South Africa and bordering Mozambique and Eswatini (IUCMA, 2022a).

4.2.1.1.1 Basin characteristics and drainage systems

The IUWMA is part of two transboundary water systems, namely the Incomati and Maputo basins, which are all shared between South Africa, Eswatini and Mozambique (IUCMA, 2020; DWS, 2021; IUCMA, 2023a). The WMA is divided by the great escarpment (along the Graskop, Sabie, Nelspruit and Barberton axis) into the western plateau and the sub-tropical Lowveld in the east, and consists of four sub-catchments, namely Sabie-Sand (approximately 9304 km^2), Crocodile (approximately 10446 km^2), Komati (approximately 8621 km^2), and Usuthu (approximately 7785 km^2) named after the respective four major rivers (Figure 4.2) (IUCMA, 2022a). The major dams in IUWMA include Nooitgedacht, Vygeboom, Da Gama, Witklip, Kwena, Driekoppies, Heyshope, Inyaka, Jericho, Klipkoppies, Longmere, Morgenstond, Primkop and Westoe.

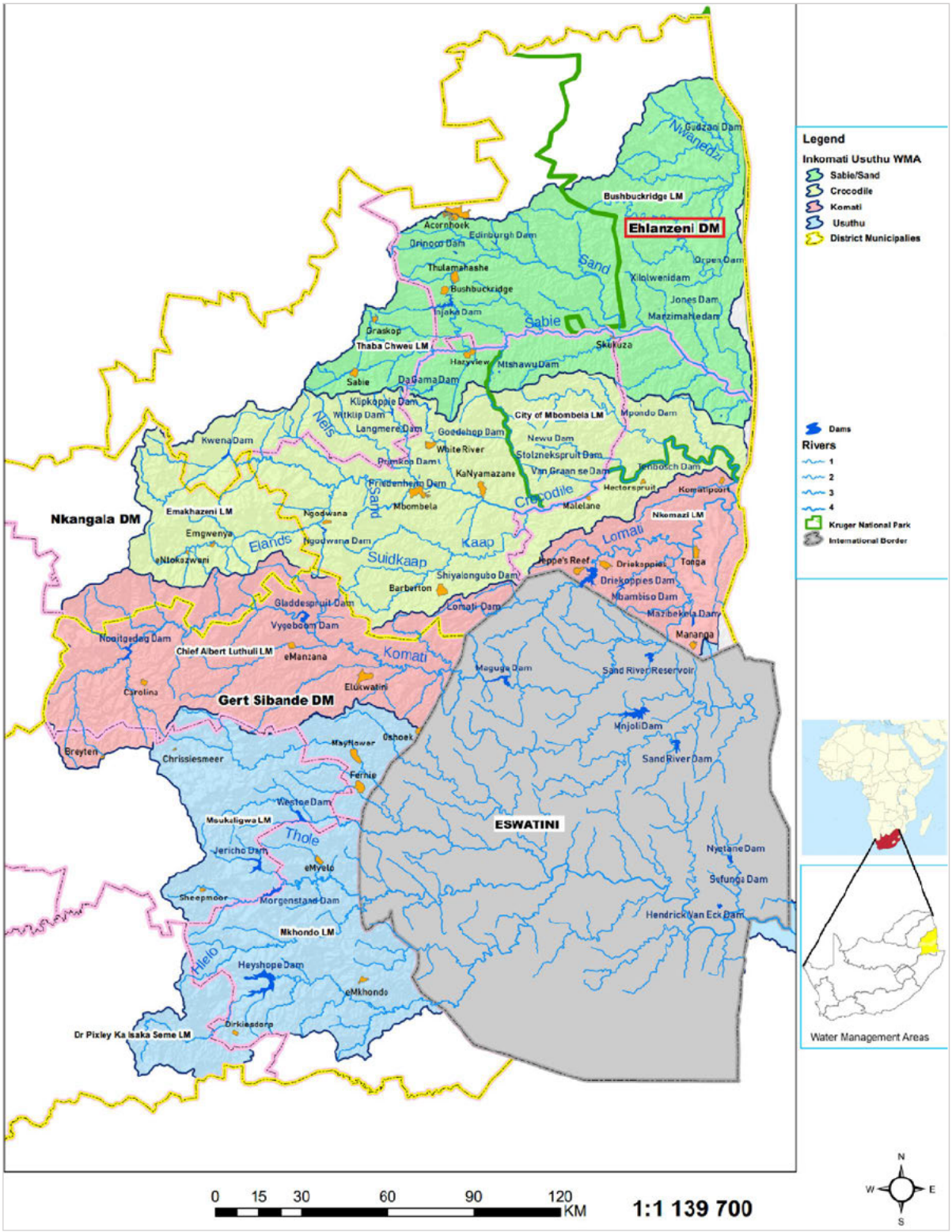


Figure 4.2: Location of **IUWMA**, its four sub-catchments (Crocodile, Komati, Sabie-Sand, Usuthu), and district municipalities, including **Ehlanzeni DM** **(see red text box)** in South Africa

4.2.1.1.2 Climate

Although IUWMA has an overall semi-arid climate (Nanfuka and Oosthuizen, 2023), it has a diverse climate due to changes in altitude in the two topographic areas, the Highveld and Lowveld (IUCMA, 2019; EDM, 2021; Mcinga, 2022). The seasonal rainfall (wet summers, dry winters) varies spatially and temporally in the catchment, ranging from 400 mm/yr in the east, which is lower and hot, has better soils and accommodate relatively more poor people, to 1200 mm/yr in the west (IUCMA, 2022a). Annual evapotranspiration generally increases from east (1800 mm/yr) to west (2200 mm/yr) (Jovanovic *et al.*, 2015; EDM, 2021; Heidi van *et al.*, 2022; Roselt and Mabila, 2022).

4.2.1.1.3 Demography

IUWMA is home to an increasing (1.3% per annum) population of approximately 2.5 million people (2022) whose average household size is 3 to 4 people, and the majority live in rural areas (Stats SA, 2022c; Stats SA, 2023a). IUWMA covers parts of three districts and nine local municipalities (Table 4.1) (Vester, 2019).

Table 4.1: Socioeconomic inequality in IUWMA's constituent districts and local municipalities (MPG, 2015; Stats SA, 2019; Vester, 2019; COGTA, 2020b; COGTA, 2020c; COGTA, 2020d)

Boundary	Fully enclosed	Gini index (2019)
Ehlanzeni DM	*No*	*0.602*
City of Mbombela LM	Yes	0.62
Bushbuckridge LM	No	0.57
Thaba Chweu LM	No	0.61
Nkomazi LM	Yes	0.58
Nkangala DM	*No*	*0.602*
Emakhazeni LM	No	0.57
Gert Sibande DM	*No*	*0.60*
Chief Albert Luthuli LM	Yes	0.59
Mkhondo LM	No	0.59
Dr Pixley Ka Isaka Seme LM	No	0.61
Msukaligwa LM	No	0.59

DM = district municipality; LM = local municipality

Due to its location in a socioeconomically unequal country (South Africa, Gini index of 0.63) and province (Mpumalanga, Gini index of 0.604), IUWMA and its constituent districts and local municipalities have highly imbalanced income distributions (Table 4.1) (MPG, 2015; COGTA, 2020b). The inequality in IUWMA is partly due to the historical apartheid divisions, structural inequality and impoverishment, and this potentially causes disparities between social groups in access to strategic resources such as water and sanitation, productive land, and supporting infrastructure for effective farming practice (MDEDT, 2011; IUCMA, 2020).

4.2.1.2 Ehlanzeni District (Ehlanzeni DM)

4.2.1.2.1 District geography

The Ehlanzeni DM is a Category C municipality (has municipal executive and legislative authority in an area that includes more than one municipality) and the second largest of the three district municipalities in Mpumalanga Province in South Africa (Figure 4.2) (COGTA, 2020b; EDM, 2021). Ehlanzeni DM covers an area of approximately 27895 m^2, makes up just

over a third of the Mpumalanga Province's geographical area, and consists of four local municipalities (Table 4.1). It is situated in the north-eastern Lowveld part of the province, and it is bordered by Mozambique and Eswatini in the east, sharing boundaries with Gert Sibande District in the south, Mopani and Sekhukhune Districts of Limpopo in the north, and Nkangala District Municipality in the west. Ehlanzeni DM is about 70% rural (COGTA, 2020b; EDM, 2021). The City of Mbombela Local Municipality is the capital of Ehlanzeni DM, IUWMA and Mpumalanga Province and makes up about a third of the district area at 7141 km^2. Bushbuckridge Local Municipality is the largest local municipality in Ehlanzeni DM by area at 10248 km^2. Thaba Chweu Local Municipality has an area of 5719 km^2 while Nkomazi Local Municipality covers an areal extent of 4787 km^2 (COGTA, 2020b).

4.2.1.2.2 District demographics

Although it is the second largest district municipality in terms of surface area, Ehlanzeni DM has the largest population (40%) among the three districts in Mpumalanga, hosting approximately 2.27 million people (2022), with an average household size of 3 to 4 people and an average annual population growth rate greater than 1% (Stats SA, 2018; Stats SA, 2022c; Stats SA, 2023a). Thus, majority of the population in IUWMA lives in Ehlanzeni DM (IUCMA, 2023a). Poverty is high (67.27%, 2018) in Ehlanzeni DM, with an unemployment rate of 36.69% (2019), which is higher than that of Mpumalanga and South Africa (28.21%) (COGTA, 2020b; EDM, 2021). Ehlanzeni DM and its four local municipalities have highly imbalanced income distributions (Table 4.1) (MPG, 2015; COGTA, 2020b).

4.2.1.2.3 District hydrology and climate

Ehlanzeni DM encloses the full Sabie-Sand sub-catchment and parts of the Crocodile and Komati sub-catchments, respectively (Vester, 2019). Ehlanzeni DM experiences summer rainfalls, which normally fall from October to March. The mean annual precipitation for Ehlanzeni DM ranges from around 800 mm/yr, and it varies spatially from approximately 450-550 mm/yr in the east to 1500 mm/yr at the escarpment and higher-lying areas. The maximum average temperatures in Ehlanzeni vary from 25°C (west) to 35°C (east), while the minimum average temperatures vary from 2°C in the mountainous west and more than 8°C in the Kruger National Park (COGTA, 2020b).

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

For analysing the WEF nexus in IUWMA and Ehlanzeni DM, this study applied the geospatial web-based integrative water-energy-food nexus analytical modelling tool (iWEF, https://www.iwef.app/) initially developed by Nhamo *et al.* (2020a) and further improved and enhanced by Taguta *et al.* (2023). The current version (June 2024) of the iWEF model integrates a GIS module that facilitates geospatial analytic capabilities for spatial information of the WEF nexus in case studies. In its original spreadsheet version, 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). The iWEF model supports the integrated assessment of WEF resources management by using the Analytic Hierarchy Process (AHP) multi-criteria decision-making (MCDM) (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 (e.g., 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 iWEF, calculated per annum, are presented in Table 4.2, and they are by no means a complete set of indicators of WEF resource security.

Table 4.2: The six indicators in the iWEF model (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; 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

The six indicators in iWEF were adopted as is in the spreadsheet version of iWEF which was developed for the context of southern Africa and was flexible to customize for the nature of indicators (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a). However, resource availability at higher level (e.g., national, international) is no guarantee for access at local scale (e.g., household), and vice versa. Accessibility and connection to networks of service is not a guarantee for 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 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).

The key inputs in the iWEF model were (i) stakeholders' pairwise comparison matrices (PCMs) developed from their pairwise judgements of the six iWEF indicators, and (ii) boundary delianations for the case study areas (Taguta *et al.*, 2023). To quantitatively assess the state of the WEF nexus, these six indicators are compared or ranked on their relative pairwise performance or importance against each other in a pairwise comparison matrix (PCM) by

stakeholders (key expert or non-expert or both) based on the Saaty AHP and scale (Appendix C), and sometimes supported by, if available, expert opinion, literature, or recognized databases (e.g., national statistics, World Bank, Aquastat) (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b). The Saaty AHP scale ranges from 1 (equal importance) to 9 (the highest and most significant relationship) (Saaty, 1977; Saaty, 1987). Other inputs in the iWEF model are delineations of the case study boundaries, which can be done manually in the "Map Playground" or automatically by uploading pre-existing shape files in .geojson format. 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) calculation and normalisation of indices of WEF security indicators by AHP-MCDM technique, and (iii) calculation of the integrated WEF nexus composite index. Key outputs from the iWEF model include the (i) consistency ratio (CR) value 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 indicate the relative performance of each indicator and sector, 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). More information on the background and working principle of the iWEF model, as well as the scaled categories of performance of the six WEF-related indicators and integrated WEF nexus composite index, is available in Chapter 3 (Table 3.1), Table 4.3, Mabhaudhi *et al.* (2019), Nhamo *et al.* (2020a), and Taguta *et al.* (2023).

4.2.3 Data collection

4.2.3.1 Indicator pairwise judgements as qualitative WEF nexus data

A survey instrument was used to elicit the opinion and perception of WEF-related key expert stakeholders (planners, managers, decision-makers and policymakers) on the status of the management of WEF resources in the two selected case study areas. The key expert stakeholders were targeted from the WEF-related sectors, which included water, energy, electricity, agriculture, food, irrigation, environment, and climate. For the pairwise comparison rankings of WEF sustainability indicators, key expert stakeholders from WEF-related sectors were asked, from their perception and knowledge of the case study, to qualitatively and

quantitatively pairwise compare the performance of the six indicators using the Saaty's AHP scale (Appendix C).

For each case study, the judgements from individual key expert 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 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 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., 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 judgements 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 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 involve optimisation by manual methods which are computationally demanding or with the use of simple automated tools (Benítez *et al.*, 2012). The latter techniques facilitate exploring inconsistencies in the matrix by locating and improving the most inconsistent judgment(s) and these tools include Expert Choice AHP Software (https://www.expertchoice.com/) and AHP Priority Calculator (https://bpmsg.com/ahp/ahp-calc.php), among others (Goepel, 2022). The AHP Priority Calculator for checking and improving consistency was chosen and used in this study due to its availability, free and open access, and its optimisation which is based on mathematics and captures the interconnections between the 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) checks for consistency, (ii) identifies the specific pairwise judgements that are inconsistent, and (iii) advises on ranges of consistent values for the outlier judgements. If unacceptable, these initial consistency results were presented to the participants to guide them in iteratively reconsidering and revising their pairwise judgements. In this way, the stakeholders reviewed their judgements

and validated the improvements in comparisons (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 considered because the theory of AHP does not demand perfect consistency (Forman and Selly, 2001). The initial PCMs for IUWMA and Ehlanzeni DM were inconsistent with consistency ratio (CR) values of 14.1% and 37.6%, respectively. The same stakeholders were re-engaged iteratively to revise some of their judgements systematically, and this resulted in finalised consistent PCMs (Appendix F) with acceptable consistency ratio (CR) values for IUWMA (8.3%) and Ehlanzeni DM (3.9%) (Table 4.3).

Shapefiles for delineating the case study boundaries were obtained from established sources such as South Africa's Municipal Demarcation Board (MDB, n.d.) and the Spatial Data Download Tool (DWS, n.d.).

4.2.3.2 Quantitative WEF nexus data

The quantitative data for WEF nexus security indicators to support the interpretation of the results from iWEF modelling were obtained or derived from established databases, archives and publications including those from statistical agencies (Statistics South Africa, Stats SA), government publications (reports, policies, strategies, census, surveys), and literature (Stats SA, 2016; Stats SA, 2018; IUCMA, 2019; Stats SA, 2020; Eskom, 2022; Eskom, 2023a; Stats SA, 2023c). Thus, various sources and existing open data were leveraged to synthesize and enhance knowledge of the WEF nexus from otherwise isolated domains (Sowby and Dicataldo, 2022). Data from government sources such as Stats SA is demarcated on administrative boundaries and not hydrological boundaries. Wherein the WMA does not fully align with administrative boundaries, the WMA populations were estimated by proportionally distributing the published province / district / local municipality population from the census figures over the part of the district that falls in the WMA (Aurecon, 2013). The latest comprehensive dataset for the target WEF security indicators (water availability, water productivity, energy accessibility, energy productivity, food self-sufficiency, cereal or crop productivity) for the selected sub-national case studies in South Africa was for 2016/17.

4.3 Results and Discussion

4.3.1 Status of WEF nexus in IUWMA and Ehlanzeni DM in South Africa

This sub-section presents the results from the analysis of the WEF nexus in the two case studies at two different scales (catchment and district) in South Africa.

4.3.1.1 Quantitative values of WEF security indicators in IUWMA and Ehlanzeni DM in South Africa

The quantitative values of the six indicators of the security of WEF sectors for IUWMA and Ehlanzeni DM obtained from established databases and published literature are presented in Table 4.3, together with the quantitative results from the iWEF modelling exercises.

Table 4.3: Overview of the WEF nexus indicators and iWEF results for IUWMA and Ehlanzeni DM in South Africa (2016/2017)

WEF nexus pillar	Indicator and units	Case study		Scaled categories of performance for WEF-related indicators[7]			
		IUWMA	Ehlanzeni DM	Unsustainable	Marginally Sustainable	Moderately Sustainable	Highly Sustainable
Water	Water availability (WA, m^3/cap/yr)[1,2]	886.8	882.8	WA < 1700	1700 ≤ *WA* ≤ 6000	6000 < *WA* ≤ 15000	WA > 15000
	Water productivity (WP, \$/m^3)[1,2]	4.11	4.90	WP < 10	10 ≤ *WP* ≤ 20	20 < *WP* ≤ 100	WP > 100
Energy	Energy accessibility (EA, %)[3,4,5]	87.2	92.7	EA < 20	20 ≤ *EA* ≤ 50	50 < *EA* < 90	90 ≤ *EA* ≤ 100
	Energy productivity (EP, \$GDP/MJ)[3,4,5]	0.12	0.15	EP < 0.11	0.11 ≤ *EP* < 0.2	0.2 ≤ *EP* ≤ 0.33	EP > 0.33
Food	Food self-sufficiency (FSF, %)[4]	83.9	85.6	FSS < 70	70 ≤ *FSF* ≤ 85	85 < *FSF* ≤ 95	FSS > 95
	Crop productivity (CP, kg/ha)[4]	5418.4	4675.8	CP < 500	500 < *CP* ≤ 2000	2000 < *CP* ≤ 4000	CP > 4 000
WEF	Consistency ratio (CR, %)[6,7]	8.3	3.9	>10% is considered unsatisfactory			
	Integrated WEF nexus composite index (*i*)[6,7]	0.209	0.210	0.048 ≤ *i* < 0.107	0.108 ≤ *i* < 0.167	0.168 ≤ *i* < 0.226	0.227 ≤ *i* ≤ 0.286

(Sources: Department of Water and Sanitation – DWS (1); Inkomati-Usuthu Catchment Management Agency – IUCMA (2); Eskom (3); Statistics South Africa – Stats SA (4); Government of South Africa (5); Key expert stakeholders and iWEF model (6); (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Taguta *et al.*, 2023) *(7)).*

According to the categories and levels of sustainability for the six indicators provided in Table 4.3, it is apparent that the security and sustainability of WEF resources in IUWMA and Ehlanzeni DM is overall moderately sustainable from an integrated perspective. The high socioeconomic inequality in IUWMA and Ehlanzeni DM is partially to blame for the moderate sustainability of WEF resources. High inequality causes uneven access to water and sanitation services, nutritious food, electricity, and basic services across income groups (Sulla *et al.*, 2022). Generally, areas with Gini indices higher than 35%, for example IUWMA and Ehlanzeni DM both have Gini indices of above 60%, have a 33-percentage-point higher probability of experiencing severe food insecurity. According to UNEN and UN-DESA (2020),

socioeconomic inequality intensifies food insecurity and malnutrition, and this effect can be extended to water and energy security due to the interconnections between WEF resources.

4.3.1.2 The iWEF perspective in IUWMA and Ehlanzeni DM in South Africa

The results from iWEF modelling of PCMs (Appendix F) from stakeholders in IUWMA and Ehlanzeni DM are presented in Table 4.3 and Figure 4.3.

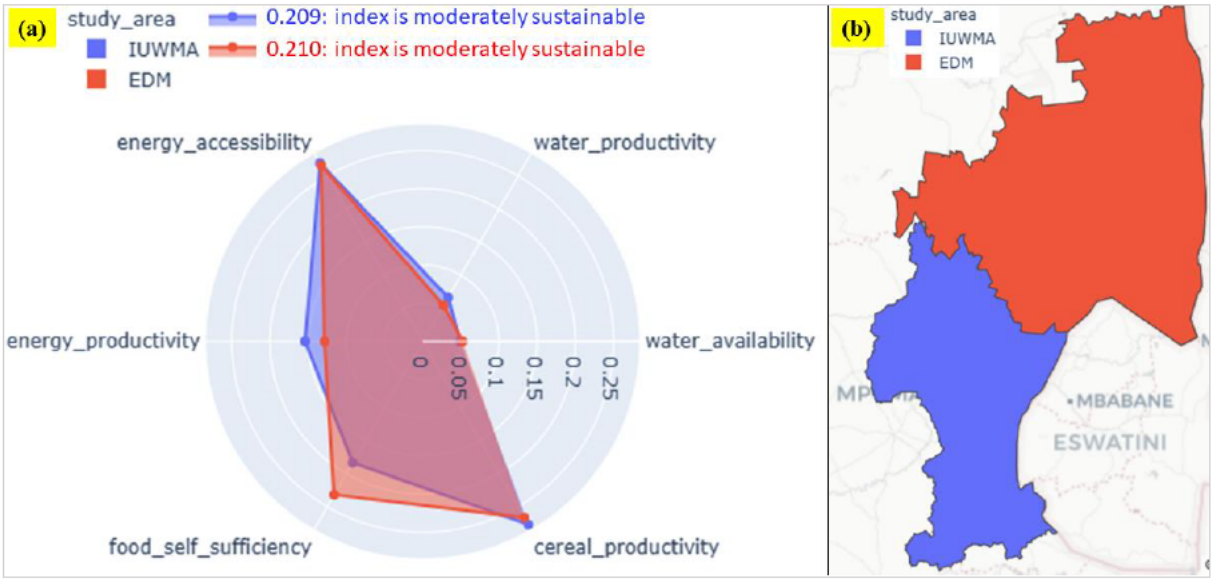


Figure 4.3: (a) Quantitative and graphical representation, and (b) spatial visualisation of the WEF nexus in IUWMA and Ehlanzeni DM in South Africa (Colour codes in the map are for distinction and identification; all normalised indices of the six indicators use the same scale in the spider diagram/radar chart/sustainability polygon)

The iWEF model graphically and spatially visualises results of WEF nexus analysis as spider diagrams and maps on the same scale for multiple case studies (Figure 4.3). This is a useful capability for spatial analysis, visualization and comparison across multiple case studies, as well as temporal analysis of nexus dynamics in planning WEF nexus scenarios over long term planning horizons.

4.3.1.2.1 IUWMA (South Africa)

With an iWEF integrated WEF nexus composite indices of 0.209 (from a maximum of 0.286 (Taguta *et al.*, 2023)) from the iWEF model run using stakeholder-based PCMs of the relative performance of six indicators in IUWMA, it is evident that the management of WEF resources is moderately sustainable, with a wide gap in integrated resources management that needs improvement from a nexus perspective (Tables 4.3, Appendix F, Figure 4.3). The irregular shape of the centrepiece in the spider diagram is evidence of unbalanced and biased management of the WEF resources in the WMA. For example, the energy and food sectors (pillars) and their indicators perform relatively well compared to the water sector (pillar) and its indicators. Cereal productivity and energy accessibility are faring better than all other indicators, followed by food self-sufficiency, energy productivity, and water availability and water productivity. These trends in performance could be attributed to different challenges and resource management practices prevalent in IUWMA, as reported by WEF-related key expert stakeholders in the catchment and from literature. These issues are presented in the succeeding sections.

(a) Water security

Approximately 80% of households in IUWMA 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 (Stats SA, 2018; MPG, 2022b). Meanwhile, the estimated reliability of water supply and sanitation services in IUWMA is 63% (DWS, 2018). The low performance in water availability is attributed to water scarcity, deficit and stress (quantity and quality) driven by population growth, urbanisation (e.g., Mbombela, White River), limited water resources, and poor water management. Other challenges include poor water quality, climate conditions, disparities in access to water, limited water storage infrastructure, heavy dependence on "run-off in the rivers", and continued and sometimes uncontrolled (unregulated) expansion of economic activities (agricultural, mining, industrial) (IUCMA, 2020; EDM, 2021; Roselt and Mabila, 2022). The status of water deficit (stress) in IUWMA sub-catchments ranges from 1% to 20%, while the availability of surface water (2177 Mm^3) within the whole WMA is less than

the demand (2981Mm^3 including ecological reserve) as the resource is overcommitted (Table 4.4) (Mallory and Magagula, 2021; Roselt and Mabila, 2022).

Table 4.4: Water budgets in IUWMA and its sub-catchments (Mallory and Magagula, 2021; IUCMA, 2023b; IUCMA, 2023a)

Water budget	**Sub-catchment**				**IUWMA**
	Sabie/Sand	**Crocodile**	**Komati**	**Usuthu**	
Surface water (Mm^3/yr)					
Supply	416.0	870.9	890.7	569.3	2177.6 to 2746.9
Demand	448.1	999.9	963.4	570.2	2981.6
Budget	-32.1	-129	-72.7	-0.9	-234.7 to -804
Groundwater (Mm^3/yr)					
Resource potential (2006)	682	707	944	597	2930
Change from 2006	678	142	79	239	1138
Available yield (present)	4	566	865	358	1793

For the sub-catchments, Crocodile is overallocated and in deficit, Lower Komati is in deficit, Upper Komati is in surplus, Sabie is approximately in balance, while Usuthu has a small surplus (Table 4.4) (Mallory and Magagula, 2021). The rate of groundwater recession over the years within the WMA has been higher than the rate of replenishment, and it remains relatively available in all sub-catchments except for Sabie-Sand (Table 4.4) (IUCMA, 2022a; IUCMA, 2023a; IUCMA, 2023b). Thus, IUWMA is water-stressed, water-scarce, and has limited water resources (Falkenmark *et al.*, 1989; Brown and Matlock, 2011). Despite efforts to establish boreholes for supplementing water from the few perennial rivers, the region suffers from a lack of adequate water infrastructure (MPG, 2020).

The hydrology and climate of IUWMA affects water availability in the region. Rainfall in the IUWMA is unevenly distributed in space and time, and the same applies to the high annual evapotranspiration (EDM, 2021; IUCMA, 2022a; Roselt and Mabila, 2022). IUWMA is highly vulnerable to climate change and variability, for instance, extreme events such as droughts (MPG, n.d.). Historical climate data for 1960–2021 shows a spatially coherent reduction in precipitation (March-April-May) in all four sub-catchments, as well as 90th percentile rainfall and rain days (DEA, 2013b; IUCMA, 2021; IUCMA, 2022a; IUCMA, 2023a). Increased annual mean and 90th percentile maximum and minimum temperatures are evident in IUWMA

(DEA, 2013b). Thus, climate change is causing extreme climate events such as multiyear droughts, which are adding to the pressure on the naturally stressed water resources (IUCMA, 2019; DWS, 2022b). The El Nino-induced drought in 2015/16 severely affected water availability in the IUWMA, and its residual effects remained until the 2019-2020 hydrological year, wherein the low water availability affected water use sectors such as agriculture and power generation (DEA, 2013b; IUCMA, 2019). Projections for climate change point to a drier and warmer future climate with higher temperatures (minimum, average and maximum), increased drought incidences and evapotranspiration, which will adversely affect the security of water resources and related sectors (DEA, 2013b; Shai, 2021; Mcinga, 2022).

The catchment's population continues to grow at an average rate of 1.3% per annum, thus exerting pressure on demand for the available water resources (DWS, 2021; Stats SA, 2022b; Stats SA, 2022a). The population dynamics are further complicated by the high influx of migrants including those from neighbouring countries (approximately 75%) and the mushrooming of mining communities and informal settlements (Mpandeli *et al.*, 2020; Roselt and Mabila, 2022; Stats SA, 2023b). Migration keeps increasing and ranks as the third influential component of demographic change in addition to fertility and mortality (Stats SA, 2023b). South Africa is a migration hotspot and Mpumalanga province hosts over 7% (5th highest out of nine provinces) of the country's migrant population (Stats SA, 2018; Mukumbang *et al.*, 2020). The demand for water and other resources and services is increasing due to urbanization, including the growth of settlements such as towns (Nelspruit, White River, Middelburg, Witbank), small towns and villages (Balzer, 2020). On the other hand, alien vegetation is currently consuming approximately 3% of available water resources (IUCMA, 2023a).

Water quality is compromised by dysfunctional water and wastewater treatment works, contamination or pollution of water (surface, groundwater) by industrial effluent and sewage (e.g., Thaba Chweu), poor municipal waste management practices (dumps, sewerage, storms water, illegal dumping, etc.), and soil erosion from agricultural activities (Shai, 2021; IUCMA, 2022a). Mining and related activities pollute, degrade, and acidify water resources (Roselt and Mpofu, 2021). Sometimes, the water is heavily polluted by coal mining effluent and acid mine drainage (AMD) to the extent that it cannot be utilised in coal-fired power stations, let alone agriculture and domestic (EDM, 2021). Other challenges to current and future water security include drying up of dams, insufficient capacity of wastewater treatment works (WWTWs) (Gert Sibande -86 ML/d, Nkangala -8ML/d), insufficient bulk water infrastructure (Gert

Sibande -18.45 ML/d, Nkangala -88.25 ML/d), illegal connections and water abstraction, and illegal mining (IUCMA, 2020; MPG, 2022b; Roselt and Mabila, 2022). IUWMA suffers from a continued lack of adequate storage infrastructure (dams, canals, off-stream storage), which is not commensurate with the growing population and demand for water infrastructure, especially in lower reaches of the catchment. At the district level, Ehlanzeni DM, Gert Sibande DM, and Nkangala DM have water storage deficits of 531 ML, 158 ML and 86 ML, respectively (MPG, 2022b).

The low water productivity in IUWMA is due to sub-optimal water use efficiencies in the various use sectors such as water distribution, domestic, energy generation, and irrigated agriculture. For example, the non-revenue water (NRW - the volume of water supplied by a water services provider [water utility], but for which it receives no income), the distribution water losses (municipal, domestic), and the irrigation water losses in IUWMA are high at 36-46.2%, 12-30% and 30-40%, respectively (Vester, 2019). Similarly, producing and sending out 1 kWh of electricity in IUWMA consumes an average of about 1.4 ℓ of water across all technologies, which is in line with but 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). The specific water consumption for electricity production in South Africa is on an increasing trend (Figure 4.4) due to the prevalence of water-intensive wet recirculation-cooled coal-fired stations in the Eskom power stations fleet, decreasing thermal efficiency and increasing age profile of the power plants (Pocock and Joubert, 2021; WRC, 2021).

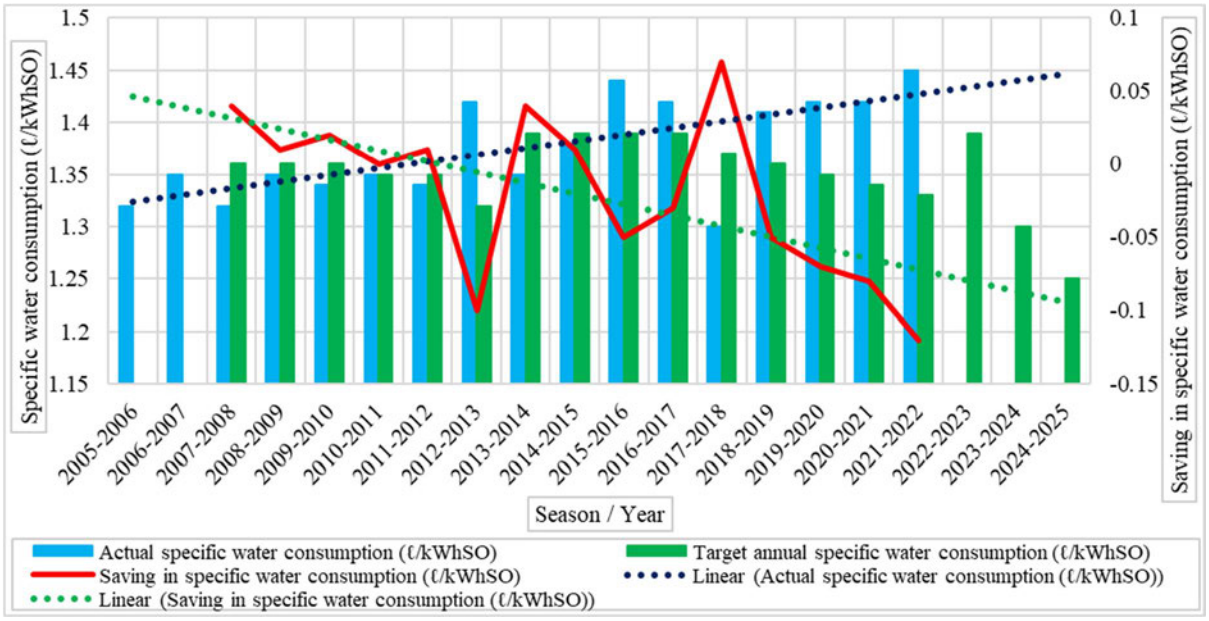


Figure 4.4: Specific water consumption or average water intensity (ℓ/kWhSO) for Eskom power stations across all technologies for the period 2006 to 2022 (actual) and 2007 to 2025 (target) (Saving in specific water consumption, ℓ/kWhSO = actual – target, thus positive is favourable) (Eskom, 2010; Eskom, 2017b; Eskom, 2022)

Accordingly, the target annual specific water consumption (ℓ/kWhSO) is decreasing, and thus, the gap between the actual and target keeps increasing (Figure 4.4). According to Pocock and Joubert (2021) and WRC (2021), specific water consumption for electricity generation increased by 0.27 ℓ/kWh (9.2%) over 16 years. Eskom's average specific water consumption of 1.42 ℓ/kWhSO in 2016/17 improved from the previous year (1.44ℓ/kWhSO in 2015/2016) but missed the annual target of 1.39 ℓ/kWhSO by 0.03 ℓ/kWhSO due to hot, dry conditions for much of the year, inefficiencies at power stations, excessive system leaks and poor water management practices (Eskom, 2017a; DWS, 2018). According to Eskom (2022), water performance is still well outside tolerance levels due to the poor technical performance of coal-fired stations and the ageing plant fleet, some of which have reached or exceeded mid-life. Poor irrigation scheduling and water-inefficient irrigation systems in smallholder farms undermine irrigation efficiency and water productivity in IUWMA (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).

(b) Energy security

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 (Stats SA, 2016). Approximately 6.7% of the population cited the cost and affordability of electricity as the top five challenges in the region (Stats SA, 2018). Most households using polluting energy sources are not connected to the national electricity grid. A cause for concern for energy security in IUWMA is the limited offtake of biogas projects (Shai, 2021).

Low energy productivity can be attributed to electricity load shedding and curtailment, which was declared a National State of Disaster in February 2023 and continues to affect livelihoods and economic activities in key sectors such as agriculture and mining (GoSA, 2023a; GoSA, 2023b; GoSA, 2023c). Electricity load shedding involves controlled and deliberate matching of electricity demand to available supply through planned rationing and rolling blackouts to protect the electricity power system from a total blackout (Eskom, n.d.-b). In 2023, South Africa experienced approximately 6947 hours 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 (The Outlier and Eskom Se Push, 2023). Energy experts in IUWMA cited challenges of maintenance delays, electrical faults, 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 power generation plants (e.g., Komati), illegal electricity connections (izinyoka), and wastage of energy at domestic/household level through use of inefficient and energy-intensive appliances.

(c) Food security

High cereal productivity in IUWMA can be attributed to good maize yields (5.81 ton/ha) and a relatively good number of households (18.2%) involved in agricultural activities, including the production of crops (grain, food) (Stats SA, 2016; Stats SA, 2020). The relatively high maize yields can be attributed to, among others, the widespread irrigation (Stats SA, 2020) and use of fertilizer in around 95% (82% synthetic, 12% organic, 1% others) of commercial farms in Mpumalanga (Shai, 2021). Marginally sustainable food self-sufficiency was due to the prevalence of running out of money to buy food and skipping a meal in the last 12 months at 23% and 15%, respectively (Stats SA, 2018). Households are involved in agriculture on small

pieces of land to produce household food and generate some household income (Stats SA, 2016). However, the future of food security is threatened by water availability and quality for agriculture and the decrease (-14.5 % from 2011) in agricultural households (Stats SA, 2016; Mcinga, 2022). Other causes for concern for food security in IUWMA include rapid urbanisation, the changes in diets and the growing middle class, growing 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 claim about 14% of high potential arable land while 40% is subject to prospecting activities (MDEDT, 2011; Shai, 2021; Mcinga, 2022). Similarly, poor soil management and mining activities continue to degrade agricultural land, and mining competes with agriculture for arable land (Mcinga, 2022). Thus, for the same arable land, the agricultural sector mainly competes with the mining industry and urbanization (MDEDT, 2011; Simpson *et al.*, 2019).

Inconsistent land reform policies and water use allocations undermine agricultural productivity, especially among smallholder irrigated farmers (Mcinga, 2022). Maize yield variabilities in IUWMA are significantly positively correlated to agrometeorological variables (Simanjuntak *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 between 19–65%, 11–38%, 16–42%, and 5–30%, respectively (DEA, 2013a; Olabanji *et al.*, 2021). Thus, current climate conditions are affecting food security in IUWMA, while future changes in climate will likely exacerbate hunger and malnutrition.

4.3.1.2.2 Ehlanzeni DM (South Africa)

With an iWEF integrated WEF nexus composite index of 0.210 (from a maximum of 0.286 (Taguta *et al.*, 2023)) from the iWEF model run using stakeholder-based PCMs of the relative performance of six indicators, it is evident that the management of WEF resources is moderately sustainable in Ehlanzeni DM, with a wide gap that needs improvement (Tables 4.3, Appendix F, Figure 4.3). The irregular shape of the centrepiece in the iWEF spider diagram is evidence of unbalanced management of WEF resources. For example, the food sector (pillar

and its indicators) outperforms the energy sector (pillar and its indicators), followed by the water sector (pillar and its indicators). Cereal productivity, food self-sufficiency and energy accessibility are faring relatively well, followed by energy productivity, while water availability and water productivity are performing relatively poorly. These moderately sustainable levels of performance in WEF indicators and the WEF nexus are due to the current challenges and management practices highlighted by key expert stakeholders in Ehlanzeni DM and the literature. These issues are discussed in the succeeding sections.

(a) Water security

About 20% of the population in Ehlanzeni DM lack access to safe drinking water, with about 12% drinking water from rain-water tanks, water carriers or tankers, and flowing water (streams, rivers) (Stats SA, 2018). According to the Falkenmark indicator of water stress, Ehlanzeni DM is water-scarce (Falkenmark *et al.*, 1989; Brown and Matlock, 2011; Liu *et al.*, 2017). With existing and required storages of 614.32 ML and 1145.15 ML, respectively, Ehlanzeni DM has a deficit in water storage despite having a surplus capacity of bulk water infrastructure (+88.84 ML/d) and WWTWs (+20 ML/d) (Balzer, 2020; MPG, 2022b). Other challenges to water security include high water demand (especially for agriculture), obligations for downstream water requirements and ecological flows, water losses (inefficiency), declining water availability, and pollution. Pollution in rivers is due to contamination by untreated or poorly treated discharges from WWTWs and illegal dumping of waste such as used diapers. The mushrooming of informal settlements complicates and undermines the provision of water and sanitation services (COGTA, 2020b). Water security in Ehlanzeni DM is undermined by the high non-revenue water (NRW) which is 42% in the City of Mbombela LM (EDM, 2021; Roselt and Mpofu, 2021). The district is vulnerable to climate change due to poverty, low adaptive capacity and high exposure to the effects of climatic conditions (COGTA, 2020b). To add, the district's population is projected to grow by approximately 3.7% between 2022 and 2031 which will exacerbate the water demand (EDM, 2021).

(b) Energy security

About 83.7%, 95.3%, 83.8%, and 66.3% of households in Ehlanzeni DM 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 (Stats SA, 2016). Most households using polluting energy sources are excluded from the national electricity grid. The provision of energy services and energy security is undermined by the mushrooming of informal settlements (COGTA, 2020b). Challenges cited by key expert stakeholders in the energy sector include electricity load shedding due to low reliability of supply, high tariffs (electricity prices), corruption, and crime including vandalism and theft of electric infrastructure such as cables and transformer oil. Current priorities include promoting energy-saving products and appliances such as halogen light-emitting diode (LED) lamps, ceramic stoves (instead of hot plates), thermostats, geyser timers, and insulated geysers. One expert from the energy sector mentioned that using a geyser timer and geyser blanket (insulation) in his home significantly cut their monthly electricity bill.

(c) Food security

Ehlanzeni DM performed fairly well in cereal productivity and food self-sufficiency due to high total staple maize production and yields (5.81 ton/ha), although the district specialises in production of non-staple crops such as vegetables (tomatoes), citrus fruits (oranges, lemons, naartjies), subtropical fruits (bananas, avocados) and tree nuts (macadamia nuts) (Stats SA, 2020). The relatively high maize yields can be attributed to, among others, the widespread irrigation and use of fertilizer especially in commercial farms (Stats SA, 2020; Shai, 2021). Food self-sufficiency is relatively high in Ehlanzeni DM due to the involvement of 40% of total households in agricultural activities including the production of livestock, poultry, grain and food crops, fruits, and vegetables, mainly for consumption and income generation (Stats SA, 2016; Stats SA, 2018). Another contributing factor could be the residual effects of the reprioritisation of agriculture by the South African government in 2010/2011 for food security and poverty alleviation (du Toit *et al.*, 2011). However, major challenges in the food sector include increases in food prices due to inflation, land and river degradation (e.g., due to sand mining), and lack of land tenure security (COGTA, 2020b). Climate-induced challenges include unpredictable weather, floods, increasing temperatures, and droughts. Experts across all sectors concurred that the lack of infrastructure affects WEF resources' security. During droughts and other water scarcity events, water resources are rationed according to priority.

4.3.1.2.3 The scale effect on WEF nexus

Although the purpose of this study was not to compare but to assess the state of the WEF nexus at the two different planning, water allocation and service delivery scales, i.e., catchment and district, some differences were noted in WEF nexus performances between IUWMA and Ehlanzeni DM, both in indicators of WEF security and in the integrated WEF nexus composite index (Table 4.3, Figure 4.3). This can be attributed to the scale effect between Ehlanzeni DM and IUWMA, since a larger portion (approximately 57.6%) of the former is part of the latter (Figure 4.2). Scale refers to the size of the analysis unit or the spatial extent of the study/implementation area, while the scale effect refers to the fact that different analysis results can be obtained when using coarser/finer analysis and measurement units (Sankey, 2015; Chen *et al.*, 2019; Ge *et al.*, 2019). In this case, the scale effect can arise from characteristic conditions including demography (population, population density, household size), agrometeorology (climate, hydrology, soils), 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 resource supply, demand and management. While Ehlanzeni DM is just one district municipality partly overlapping with the larger IUWMA (Figure 4.2), the latter comprises Ehlanzeni DM, its four local municipalities (City of Mbombela, Bushbuckridge, Thaba Chweu, Nkomazi) and two other district municipalities namely Gert Sibande and Nkangala and their constituent local municipalities. Accordingly, the WEF system in IUWMA is an integration of the WEF system in Ehlanzeni DM intertwined with WEF systems and subsystems in the two district municipalities. Thus, the state of the WEF nexus in IUWMA is an aggregated combination of the state of WEF nexus in Ehlanzeni DM and the other two district municipalities. To add, the two case studies are not exact replicas and thus cannot be expected to have exactly similar states of the WEF nexus.

IUWMA has slightly lower water availability due to a lower range in mean annual precipitation of 400 mm/yr in the east to 1200 mm/yr in the west, compared to a higher range in mean annual precipitation of in Ehlanzeni DM of 450-550 mm/yr in the east to 1500 mm/yr at the escarpment and higher-lying areas (COGTA, 2020b; IUCMA, 2023a). The water productivity for Ehlanzeni DM is slightly higher than that for IUWMA because the crops in the former include sugarcane, vegetables (tomatoes, carrots), and fruits (oranges, lemons, naartjies, bananas) which have a lower water footprint (higher water productivity) than the crop mix in the latter which includes cereals (maize) and pulses and oil crops (soya beans) with a higher water

footprint (lower water productivity) (Mekonnen and Hoekstra, 2011; Amarasinghe and Smakhtin, 2014; Midmore, 2015; Hendriks *et al.*, 2016; Stats SA, 2020). The crop mix in Ehlanzeni DM includes horticultural crops which tend to use water-efficient irrigation systems than that for IUWMA which includes field crops. Such water-efficient irrigation systems tend to use less water and hence less energy for pumping water which may translate to higher energy productivity in Ehlanzeni DM than in IUWMA, due to the close linkages between water supply and energy consumption in the irrigation sector (Tarjuelo *et al.*, 2015). Ehlanzeni DM leads IUWMA in energy accessibility due to high connection of households to natural electricity grid networks in the former than the latter (Stats SA, 2016; Stats SA, 2018). Despite the focus on commercial horticultural crops in Ehlanzeni DM, its food self-sufficiency is slightly higher than in IUWMA because the latter has a higher proportion (40%) of households involved in the production of food (livestock, poultry, grains, fruits, vegetables) than the latter (18.2%) (Stats SA, 2016; Stats SA, 2018). IUWMA leads Ehlanzeni DM in crop productivity especially for staple grains/cereals due to higher yields that were reported in other district municipalities including Gert Sibande (5.31 ton/ha) and Nkangala (6.26 ton/ha) and their local municipalities including Chief Albert Luthuli (5.34 ton/ha), Dr Pixley Ka Isaka Seme (6.12 ton/ha), Mkhondo (7.12 ton/ha), Emakhazeni (5.35 ton/ha) (Stats SA, 2020). Thus, WEF nexus dynamics are scale and context-specific and should be analysed and addressed accordingly.

4.3.1.2.4 Summary

The findings from this study concur with those from previous studies, especially on the moderate sustainability in the management of WEF resources across scales from a nexus perspective in South Africa. It was reported that the management of WEF resources in South Africa 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). Studies 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.*, 2023a; Dlamini *et al.*, 2023b).

4.3.1.3 Improving the status of the WEF nexus in IUWMA and Ehlanzeni DM in South Africa

In IUWMA and Ehlanzeni DM, there is a need to manage resources in ways that simultaneously and collectively improve the (i) indicators of resource security (Tables 4.3), (ii) indices of performances for the WEF sectors (Appendix F), and (iii) centrality of their centrepieces in iWEF spider diagrams (Figure 4.3). Entry points for intervention and areas of prioritization can be identified from a combination of findings in the spider diagrams (Figure 4.3, Appendix F) and Table 4.3. The sectors and indicators in need of priority intervention are those with plot points that are close to the centre (0, origin) of the spider diagram (Figure 4.3), i.e., they have the lowest values of normalised indices (Appendix F), for example, the water sector specifically, water availability and water productivity in both case study areas. However, any WEF-related intervention efforts need to be planned and implemented from a nexus perspective so as not to cause cross-purposes and trade-offs with other sectors and pillars as highlighted for the ongoing, operational and planned WEF-related practices and initiatives in IUWMA and Ehlanzeni DM in South Africa (Table 4.5).

Table 4.5: Summary of ongoing, operational and planned WEF-related practices, initiatives and their potential WEF-related synergies and risks across scales in IUWMA and Ehlanzeni DM in South Africa

Water			Energy			Food		
Practice / intervention	**Nexus opportunities**	**Nexus risks / trade-offs**	**Practice / intervention**	**Nexus opportunities**	**Nexus risks / trade-offs**	**Practice / intervention**	**Nexus opportunities**	**Nexus risks / trade-offs**
Groundwater use	Deep aquifers; sand rivers	Groundwater depletion	Decommissioning and repurposing of coal-fired power stations	Water savings; Improved air quality and human health	Reduced energy supply	Irrigation expansion (3000 ha); Irrigation rehabilitation (11139 ha)	Improved food production and enery and water productivity	Increased water and energy demand
Wastewater treatment and reuse (e.g., mining, forestry)	Functional wastewater treatment plants More water for irrigation availed	Environmental health; Insufficient and dilapidated wastewater treatment plants; Energy scarcity	Recommissioning and repowering of coal-fired power plants; Fossil-based power stations (e.g., diesel, gas, LNG)	Stabilised energy supply	Poor air quality and human health, and human death	Irrigation modernization	Water savings	Increased energy consumption
Rainwater harvesting and storage, construction of small dams	Water availability and supply		Production of green hydrogen energy	Increased energy supply	Reduced water supply; Competition for land	Waste-to-food (sludge beneficiation manure)	Urban waste, wastewater; Agricultural waste	Insufficient and dilapidated wastewater treatment plants; Energy scarcity
Removal of invasive alien vegetation	Water saving; Biomass for energy	Disruption of ecosystems	Electrification	High solar potential; Grid capacity; Clean cooking	Insufficient electricity generation and supply	Community food and nutrition gardens; Urban agriculture; Controlled environment agriculture (e.g., greenhouses, hydroponics, aquaponics, aeroponics)	Food security and nutrition	Water and energy scarcity
Improving water use efficiency in non-agricultural	Water saving		Renewable energy (solar PV, battery energy	High renewables potential;	Competition for land;	Soil and water conservation (e.g., climate smart	Increase productivity, enhance	Labour intensive, e.g., manual

sectors (e.g., mining, domestic, retrofitting cooling systems in power plants)			storage, solar-powered water pumps and irrigation, solar water heaters)	Additional energy and water resources	Groundwater depletion	agriculture, conservation agriculture	resilience, climate mitigation, soil and water conservation	conservation agriculture
Expanding and rehabilitating water (including bulk) and wastewater infrastructure (including decentralised)	Clean water supply; Treated wastewater reuse	Water and energy scarcity	Waste-to-energy (biogas digesters, landfills, cogeneration)	Urban waste, wastewater; Agricultural waste	Insufficient and dilapidated wastewater treatment plants; Energy scarcity	Agroecology (agro-forestry, tolerant and resistant varieties, small grains, underutilised crops, livestock production)	Food security and nutrition	Water for livestock
Water reallocation and inter-catchment transfers	Increased water supply	Decreased water supply; Increased energy demand	Improving energy efficiency (generation and use)	Energy saving; Water saving		Soil fertility management	Improved soil health and crop productivity	
Water and land reform	Increased small-scale agricultural production	Land fragmentation	Modern clean cooking (e.g., stoves, LPG, biogas)	Improved air quality and human health; Conservation of forests		Postharvest management (e.g., processing, food loss reduction); Community nutrition centres	Food security and nutrition	
Reduction in the per capita consumption and non-revenue water	Water saving; Energy saving		Mine land rehabilitation and repurposing	Increased energy supply and agricultural production		Farm mechanization	Increased agricultural production	Energy insecurity

Sources: Key expert stakeholders; (MDEDT, 2011; GoSA, 2012; DAFF, 2015; DNA Economics, 2016; Eskom, 2017b; DWS, 2018; GoSA, 2019; IUCMA, 2019; Balzer, 2020; DTIC, 2020; GoSA, 2020; MPG, 2020; DWS, 2021; EDM, 2021; IUCMA, 2021; Nyamadzawo, 2021; African Energy Chamber, 2022; DALRRD, 2022; DEDT-MPG, 2022; DTIC, 2022; DWS, 2022a; EDM, 2022a; EDM, 2022b; IUCMA, 2022b; MDARDLEA, 2022; MPG, 2022b; MPG, 2022a; Nyamadzawo, 2022; DWS, 2023; EDM, 2023).

Ideally, interventions should avoid sacrificing and compromising but be synergistic and accrue improvements in all sectors and pillars. A balanced and improved efficient management of WEF resources can be achieved by (i) enhanced collaboration between sectors for cross-sectoral planning and implementation of WEF endeavours, (ii) reallocation of and reprioritization of WEF resources and sectors, respectively, and (iii) pursuing and exploring bespoke integrated regionally differentiated and contextually or locally specific programs, projects and actions that potentially drive towards collective security of WEF resources. Such measures should prioritize management of WEF resources for enhanced efficient utilization and supply.

4.3.1.3.1 Water

The construction of proposed dams especially in highly overallocated sub-catchments such as Crocodile can improve water yield and address water shortages, for example Boschjeskop Dam (Nels River), Mountain View Dam (78 Mm^3/annum, Kaap River), Strathmore Dam and other off-channel storage facilities (IUCMA, 2023a). Groundwater can buffer water scarcity in even the driest of climates (e.g., IUMWA and Ehlanzeni DM), for survival, social, economic and environmental benefits, climate change adaptation and achievement of the SDGs (UN, 2022). Since surface water is overallocated in IUWMA, potential exists to exploit groundwater whose available potential is 1793 Mm^3/yr in the catchment. At sub-catchment level, only Sabie-Sand has a very low available groundwater yield of 4 Mm^3/yr, while the rest have good available yields of 865 Mm^3/yr (Komati), 566 Mm^3/yr (Crocodile), and 358 Mm^3/yr (Usuthu) (EDM, 2022a; IUCMA, 2023b; IUCMA, 2023a). However, pumping groundwater for irrigation is more energy-intensive (about seven times) with higher resource and environmental costs (greenhouse gases) than surface water abstraction and irrigation (Jackson *et al.*, 2010; Wang *et al.*, 2012; UN, 2022).

Although the rising prevalence of netting improved on-farm water use efficiency in IUWMA, expansion and maintenance of infrastructure in existing irrigation schemes will be critical for optimising water productivity (BFAP, 2022). Irrigation is the largest user of water in IUWMA at 31% of total water demand, thus improving water user efficiency and water productivity in irrigated agriculture is likely to save a significant amount of water, for example by

modernization and proper irrigation scheduling to reduce the reported irrigation losses of 30-40% (Vester, 2019). Irrigation modernization by changing from surface to pressurised irrigation saves water at field/farm scale but may increase energy consumption for pumping and water application (Taguta *et al.*, 2022; Smith *et al.*, 2023).

Water can also be saved in IUWMA through reducing non-revenue water (NRW, 36-46.2%), distribution water losses (municipal, domestic, 12-30%), and the specific water consumption for electricity production (litres per kilowatt-hour sent out) in the coal-fired power stations. The removal of alien vegetation in IUWMA (e.g., along Sabie, Crocodile, Usuthu and Komati rivers) can potentially save 3% of available water resources with increases in the assurance of supply for run-of-river users, conservation of water quality, biodiversity and ecosystems, while the harvested biomass is a potential source of energy (Marais and Wannenburgh, 2008; Chamier *et al.*, 2012; Roselt and Mabila, 2022; Vera *et al.*, 2022; IUCMA, 2023a).

4.3.1.3.2 Energy

Another case in point is the ongoing transition to a low emissions economy through shifting towards lower-carbon sources of energy which will inevitably produce and, in many cases, perpetuate pre-existing sets of winners and losers in South Africa (Carley and Konisky, 2020). After the shutdown of the coal-fired Komati Power Station in 2022, Eskom is using the power station to pilot repowering and repurposing of power stations on Eskom land using existing infrastructure. Key components of the pilot will include the installation of an agrivoltaic plant (0.5MW), an assembly plant for containerised microgrid solar PV systems, a renewable energy training facility, an aquaponics system, community-based agricultural small, medium and micro enterprises, community entrepreneurial training, and renewable energy generation (wind, solar, battery energy storage) (Eskom, 2023b). Shutting down the Komati Power Station saved IUWMA freshwater resources (15 Mm^3 - 19 Mm^3 of per annum) while the planned closure of Camden, Grootvlei, and Hendrina in the near future will potentially save 44 Mm^3 - 53 Mm^3 of water annually (Eskom, 2017b). Other nexus benefits of shutting down coal-fired power stations in IUWMA include availability of land, climate mitigation and improved air quality due to reduced emissions (Urban-Econ Development Economists, 2021). However, shutting down the base-load coal-fired power stations and its benefits are coming at a cost to energy security and livelihoods (Eskom, 2017b; Urban-Econ Development Economists, 2021).

The planned renewable energy generation capacity of 370MW (solar 150 MW, wind 70 MW, battery energy storage 150 MW) for the repurposed Komati Power Station is too low compared to the installed coal-fired Komati Power Station generation capacity of 1000MW (125 MW capacity since 2021 until shut down), and the gap will likely undermine national grid stability and local energy security unless remedial action is taken. Similarly, the planned closure of Camden, Grootvlei, and Hendrina will cost the country a grid capacity loss of almost 4464 MW and 3149 MW of installed and nominal capacity, respectively (Eskom, 2023c; World Bank, 2023).

Hence energy security in South Africa will largely depend on the rate of replacement of the generation capacity lost in the decommissioned coal-fired power stations. With reference to 2020, the shutdown and repurposing of Komati Power Station put 4166 (out of 4270) direct permanent (257) and indirect (3909) jobs at risk, including 791 (out of 810) onsite jobs at risk (Urban-Econ Development Economists, 2021). It is yet to be seen if the livelihoods of these affected workers and communities will be restored through repurposing and repowering of Komati Power Station. By 2030, World Bank projects approximately 15000 beneficiaries including Komati workers receiving transition support (World Bank, 2023), while Eskom promises approximately 430-660 full-time jobs, 7700-8700 temporary jobs and 200 trainees annually (Eskom, 2023b; Eskom, 2023c). Thus, energy transition is a complex process that affects social equity, environmental sustainability, and economic development (Li and Zhang, 2023), while a nexus approach can unpack the complexities in energy transition, for example through a priori identification of winners and losers, and inform posteriori management of the latter (Beekma *et al.*, 2021). In that way and in decommissioning of the old and coal-fired power stations especially in IUWMA, the South African government can apply an economy-wide nexus approach to honour its promise of a 'just energy transition' (JET) towards a low-carbon, climate-resilient economy and society that maintains/improves the (i) supply and provision of energy, water and food, (ii) livelihoods including for the most vulnerable (e.g., including women, children, people with disabilities, the working class and the poor), (iii) conservation and protection of the environment (climate, ecosystems, biodiversity, water), (iv) justice (distributive, restorative, procedural), and (v) economic development (Eskom, 2017b; NPC, 2019; PCC, 2022).

IUWMA and Ehlanzeni DM are rich in renewable energy resources including solar photovoltaic, wind, biomass (forestry, sugarcane bagasse), landfill waste (waste-to-energy), biogas, and mini-hydro (MDEDT, 2011; DNA Economics, 2016; DEDT-MPG, 2022;

MDARDLEA, 2022). The deployment of renewables in IUWMA and Ehlanzeni DM is favoured by prevailing enabling conditions including available grid capacity (6520 MW), Renewable Energy Development Zones (REDZs), Independent Power Producers Procurement Programme (IPPPP), tax incentives (e.g., the 25% rooftop solar tax incentive), net metering, high licencing cap (100 MW), wheeling and energy trading regulations and feed-in tariffs (GoSA, 2022a; Nyamadzawo, 2022; National Treasury, 2023). IUWMA has an average daily specific photovoltaic power output (PVOUT) of 4.53 kWh/kWp and an average daily global horizontal irradiation of 4.87 - 5.43 kWh/m² which is almost 84% of the country's highest potential in Northern Cape (ESMAP, 2020; Nyamadzawo, 2022; Solargis, n.d.; Solargis and ESMAP, n.d.). The wind speed in Mpumalanga province ranges between 4 m/s and 7 m/s at 100m above ground level (Nyamadzawo, 2022). The Mpumalanga region boasts of 6520 MW available grid capacity and is expected to be allocated with 2600 MW of renewable energy projects under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) by 2030 (Nyamadzawo, 2021; Nyamadzawo, 2022). As of December 2023, the Independent Power Producers Procurement Programme (IPPPP) in South Africa had 95 operational Independent Power Producers (IPPs) with 6180 MW added grid-connected generation capacity. These projects generated 110022 GWh which is enough to power more than 33.1 million households, and they realised water savings of at least 125.5 Mm^3, offset 106.2 Mton CO_2, and created 81043 job years (DMRE, 2023). At a small scale, Eskom is deploying smart containerised microgrid solutions comprising battery, PV and inverter technology for the supply and storage of electricity in rural areas. A total of 21 containerised microgrids were installed during the 2022/23 financial year, while 216 microgrid installations were targeted over the subsequent five years (Eskom, 2023b). Waste-to-energy generation plants can be upscaled following the success of Malelane Sugar Cogeneration Plant (26.4MW; TSB Sugar) which uses bagasse (waste fibre from sugarcane) to generate electricity, and the Ngodwana Biomass Power Station (25 MW; Sappi) from REIPPPP Bid Window 4 which uses waste wood chips and forestry products (paper and sawmill) to generate electricity (Shai, 2021).

Hydrogen is not an energy source but an energy vector (or chemical energy carrier) that is used to convert, store, and then release and distribute energy (Webber, 2007). The electrolysis of water with renewable energy to produce green hydrogen and oxygen has a lower carbon footprint (0 kg CO_2-eq/kg H_2) than the production of grey (fossil fuel based without carbon capture, utilization and storage) and blue (fossil fuel based with carbon capture, utilization and

storage) hydrogen, but the former process is more costly and energy- and water-intensive than the latter two conventional production methods (Metcalfe *et al.*, 2020; AbouSeada and Hatem, 2022; IEA, 2023; Weidner *et al.*, 2023). The production of green hydrogen in renewable-rich, energy- and water-scarce IUWMA will likely exacerbate water and land scarcity, and thus it is recommended for the country to either import hydrogen to meet domestic needs or produce hydrogen with non-potable water resources (seawater, wastewater) (Ajanovic *et al.*, 2022; Fairley, 2023; Kelly and Roos, 2023; Tonelli *et al.*, 2023). However, more localised studies are needed to interrogate, from a nexus perspective, the production of green hydrogen to identify its likely implications especially trade-offs on strategic resources (e.g., water, energy, food, land), for crafting strategies to manage risks, and optimize on synergies if they exist (CER, 2023).

Energy savings (approximate 218GWh/annum) that were accrued from the National Solar Water-Heating Programme (443 486 out of target 1 million households) led to reduction in coal use (0.53 kg/kWh), water use (1.40 l/kWh), and environmental pollution from emissions such as ash, particulate, carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrous oxides (NO_x) (Eskom, n.d.-a). Thus, further implementation of this program to reach or surpass the target of 1 million households will accrue further benefits in resource savings (water, energy), environmental conservation and climate change mitigation. This will also accrue co-benefits of provision of a constant, cheap source of heated water, reduction in the use of polluting fuels such as paraffin and wood, stabilization of the electricity grid, alleviated energy poverty, improved energy security and human health, savings in time and money, as well as reduced household vulnerability to shocks, stressors and seasonal variability (Wlokas, 2011; Thobejane *et al.*, 2019).

4.3.1.3.3 Integrated solutions, cross-cutting issues and decentralization

From an integrated nexus perspective, previous research has shown the potential opportunities for improving the status quo and future WEF resource security in South Africa through integrated transformative management approaches, including the WEF nexus planning. Tantoh and McKay (2023) found that improving the WEF nexus for smallholder farmers in the Eastern Cape, including for food security and more income, must go beyond increased access to land and water but should include access to agricultural extension services, markets, cost-effective

transport and capital. On the other hand and from a nexus perspective, 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.

In efforts meant to improve the security of WEF resources for all and their efficient use, equal consideration needs to be made for climate action (mitigation, adaptation), closing the rural-urban development divide, and redressing historical injustices, inequalities and inequities through harmonization of objectives and activities for just, fair, socially equitable, culturally acceptable, gender-sensitive, and environmentally friendly transitions and transformations. Balancing these multiple objectives including resource security, environmental and human health, and sustainability is a dauntingly complex task that can be simplified by use of the transformative and polycentric nexus planning which seeks to systematically unpack complexities for assessing and managing interlinked systems without amplifying trade-offs and cross-sectoral risks (Scott, 2017; Mabhaudhi *et al.*, 2021; Nhamo and Ndlela, 2021; Nhamo *et al.*, 2022). Given its widespread attention and traction in almost all spheres of life, the WEF nexus approach must not perpetuate but address the underlying social ills of disparities in WEF resources security. Since feedback loops exist between the high socioeconomic inequality and WEF insecurity in South Africa, closing the income gap between social groups may address the gaps in the provision of water and sanitation services, malnutrition, slow progress in expanding access to electricity, and uneven access to basic services (UNEN and UN-DESA, 2020; Sulla *et al.*, 2022). Although the inequality in IUWMA and Ehlanzeni DM is partly due to the historical apartheid divisions, deliberate efforts for poverty reduction and redistribution of strategic productive resources (land, water, energy), services (sanitation) and supporting infrastructure for effective farming practice can potentially reduce inequality (MDEDT, 2011; IUCMA, 2020). Sometimes, it may be necessary to reallocate resources to ensure equitable and just access before or in parallel with improving efficiency and productivity. According to Young (2021), the availability of resources is necessary and determines, but not sufficient, their access, use, and stability. IEA (2022) reiterates that universal access to electricity is both a (i) fundamental and moral imperative and (ii) prerequisite for a pathway to net-zero emissions because without affordable electricity, underserved populations will continue to rely on dirtier sources of energy for cooking, heating, transport, and lighting. The same argument can be extended to advocate for universal access to water and food.

Consideration must be given to context-specific interventions including pro-rural decentralised and distributed solutions (UNDESA, 2021; African Energy Chamber, 2022) for off-grid communities such as those in rural and peri-urban areas in IUWMA and Ehlanzeni DM (70%) to ensure that "no one is left behind" and "the furthest behind are reached first" as pledged in the 2030 Agenda for Sustainable Development (UNGA, 2015). In many countries, challenges still exist in extending services for access to strategic resources to rural areas, resulting from inequalities and injustice (UN, 2023). For example, the cost of providing grid connections has increased in South Africa as the service areas become more remote (GoSA, 2019). Such 'last mile' underserved populations living in marginalised, hard-to-reach, cut-off and remote areas or regions, for example, in rural, urban or peri-urban areas (urban slums, townships) usually lack access to adequate WEF resources due to lack of connection to national or regional networks of resource supply such as the water network, electricity grid, and food supply corridors (Rabta *et al.*, 2018; Faal *et al.*, 2022). Several factors contribute to the lack of access to basic services and resources, including economics (cost), physical distance, cultural or belief systems, values and prioritisation, geography (isolation, terrain), low population density and dispersed households, low energy demand, poverty (fiscal deficit, generation resources), poor or non-existent infrastructure (inaccessibility), local society perspective (Rabta *et al.*, 2018; Faal *et al.*, 2022). Hence, such underserved populations exploit natural ecosystems for resources to satisfy their water, energy and food demands for survival, usually leading to serious depletion and degradation (Lahimer *et al.*, 2013). As such, deliberately targeted strategies for the poor and vulnerable including some listed in Table 5 promote the protection and conservation of natural capital (UNDESA, 2021)[17]. Similarly, the WEF nexus approach is a means to contain the expected high future urbanisation of 70% by 2050, by narrowing the rural-urban divide and advancing rural development that would allow rural populations to reach the urban standard of living without having to migrate to urban areas (Ritchie and Roser, 2018; UNEN and UN-DESA, 2020; UNDESA, 2021; OECD and FAO, 2022). Even in urban areas, innovative decentralised WEF technologies potentially alleviate the pressure on constrained centralised WEF systems, such as over-allocated water systems and inadequate energy generation systems (Roselt and Mabila, 2022).

While the case study focused on two sub-national scale areas in South Africa, the findings from this study apply to sub-national scale areas in South Africa and other countries in southern

[17] United Nations (UN). Rethinking rural development for achieving SDGs. https://sustainabledevelopment.un.org/index.php?page=view&type=20000&nr=7361&menu=2993

Africa, specifically, and the global South, broadly. These countries share a similar history, context, and developmental challenges, and the same can be said about their typical sub-national scales (Nhamo *et al.*, 2018; Mabhaudhi *et al.*, 2023). For example, more than half of the countries in southern Africa including Madagascar, Malawi, Mozambique, Namibia, South Africa, Zambia and Zimbabwe are either at risk of or being affected by electricity load shedding (Metivier, 2023), while the El Niño drought (2023-2024) is affecting the previously listed countries and Angola and Botswana (RIASCO and OCHA, 2024). Approximately 70% of smallholder farmers in southern Africa heavily rely on rainfed agriculture for their food and livelihood (Mabhaudhi *et al.*, 2019; Brookings Institution, 2023; Nyoni *et al.*, 2024), and therefore the 2023-2024 El Niño drought was declared a national disaster in Malawi, Zambia, and Zimbabwe (Moyo, 2024; Murwira, 2024).

4.4 Limitations of Study

It is acknowledged that the version of iWEF model (June 2024) used in this study includes a subset of domains of resource security for water (availability, use / utilization), energy (accessibility, use) and food (productivity, sufficiency), but 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). Despite this limitation, it 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 for the iWEF model, i.e., the AHP, is usually criticised for subjectivity. However, the AHP technique provides the objective structured mathematics to systematically process the inescapably subjective and personal preferences of an individual or a group in making a decision (Saaty and Vargas, 2012b). The AHP has found application in many fields and various specialties that face multicriteria problems that require aggregating distinct indicators and monitoring 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).

4.5 Conclusion and Recommendation

The objective of this study was to assess the state of the WEF nexus using mixed methods at catchment and district scale in southern Africa using IUWMA and Ehlanzeni District Municipality in South Africa as case studies. The qualitative research methods constituted interviews and discussion guides administered to key expert stakeholders in the WEF-related sectors in the case study areas. The quantitative research methods included conjunctive use of the iWEF model and established databases, reports and literature for reviewing secondary data and collecting information related to water, energy and food resources supply, demand, utilization and management.

To conclude, the state of WEF nexus is moderately sustainable in IUWMA and Ehlanzeni DM due to unbalanced management of WEF resources, as evidenced by frequent water outages/rationing, incidence of waterborne diseases (e.g., cholera), frequent electricity load shedding, hunger and malnutrition, coal mining-land-water-environment trade-offs, and the stagnating and slow progress in achieving SDGs. Prioritisation of interventions in IUWMA and Ehlanzeni DM including irrigation development, decommissioning of coal-fired power stations and production of hydrogen have potential opportunities and risks which should be understood and managed from a nexus perspective. Similarly, dam construction, renewable energy, removal of alien vegetation, solar water heaters, groundwater use and WEF systems co-location are scalable interventions that can potentially achieve multiple socioeconomic, environmental and livelihoods objectives in IUWMA and Ehlanzeni DM and other areas with similar context in southern Africa and beyond. Thus, the iWEF model is useful for bringing together WEF stakeholders to establish 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. However, the six indicators in the iWEF model potentially fail to capture all key pillars of WEF resource security and thus give an incomprehensive picture of quality of WEF resource security.

Going forward, synergies and trade-offs of current practices and planned and ongoing WEF-related interventions need to be quantified for their economy-wide implications to inform upscaling. Promising integrated WEF solutions need piloting to demonstrate and measure the multisector impacts in the real world and inform the accelerated implementation of the WEF nexus approach for sustainable development. WEF nexus studies in IUWMA and Ehlanzeni

DM should give due consideration to climate and mining nodes which are part of the environmental dimension of the nexus. Preferably, the iWEF model needs to be further improved for flexibility and adaptability in the number and nature of indicators.

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5 THE STATUS OF THE WATER-ENERGY-FOOD NEXUS AT SUB-NATIONAL SCALES: THE CASE OF ZIMBABWE

Abstract

The government of Zimbabwe repeatedly committed to ensure universal security of water-energy-food (WEF) resources within the limits of available resources. However, its citizens and economy continue to suffer from the scarcity and insecurity of WEF resources which has undermined Zimbabwe's progress towards achieving WEF-related Sustainable Development Goals (SDGs 2, 6, 7). Addressing the triple crises of WEF resources insecurity requires shifting from the "business-as-usual" sectoral planning of WEF resources towards integrated planning approaches to resources management. Although Zimbabwe acknowledges the value of integrated approaches in its resource management policy and governance, the Integrated Water Resources Management (IWRM) approach faced its share of challenges. The adoption and implementation of the integrative water-energy-food (WEF) nexus approach at sub-national scales in southern Africa, including Zimbabwe, is slow due to lack of empirical evidence, practical tools and guidelines. This study applied mixed methods (observations, literature, stakeholder engagement, WEF nexus modelling) to assess the state of the WEF nexus at catchment and district scales in southern Africa using Mzingwane Catchment and Umzingwane District in Zimbabwe as case studies. An analysis of inputs from key expert stakeholders with the geospatial web-based integrative water-energy-food nexus analytical modelling tool (iWEF) yielded integrated WEF nexus composite indices of, respectively, 0.189 and 0.194 out of a possible 0.286 maximum, in Mzingwane Catchment and Umzingwane District. Thus, as initially hypothesised, the management of WEF resources in both case studies is moderately sustainable, with an overall low WEF nexus performance and an unbalanced management of WEF resources. Prioritised interventions such as managed solar photovoltaic pumping of groundwater and sand rivers, co-locating renewable energy production with water and food, and biogas production can significantly improve WEF security for all in Mzingwane Catchment and Umzingwane District. From a nexus perspective, such WEF-related interventions need to be robust, scalable and contextualised, for example, by including decentralised options that can bring sustainable development to the rural areas of Mzingwane Catchment and Umzingwane District. The planning of such bespoke solutions can benefit from WEF nexus modelling and scenario planning (what if) with tools such as the iWEF model

which brings together WEF-related stakeholders in co-planning and harmonising activities among the WEF sectors. Future recommended work includes piloting for demonstrating and upscaling promising integrated WEF solutions and taking stock of progress made in implementing the WEF-related policies, resource management approaches and governance models in Zimbabwe.

Keywords: global South, iWEF, sub-national, nexus, resource management, SDG, Zimbabwe

5.1 Introduction

The Government of Zimbabwe is committed to water, energy and food (WEF) security for all through the the UN Agenda 2030 for Sustainable Development (UNGA, 2015) and its national policy framework which includes the National Development Strategy 1 (NDS1, 2021-2025). However, the continued depletion and degradation of WEF and land resources amidst climate change threaten economic development, livelihoods, and the ability to achieve the Sustainable Development Goals (SDGs) and access to WEF resources for all (FAO, 2017; Leal Filho *et al.*, 2018; Sachs *et al.*, 2023). The SDG Index for Zimbabwe (55.6%) is below the global (66.7%) and regional averages (Southern African Development Community, SADC: 56.4), and similar trends are evident for achievement of SDGs related to water (SDG#6: clean water and sanitation), energy (SDG#7: affordable and clean energy) and food (SDG#2: zero hunger) (Sachs *et al.*, 2023).

About 84.4% of households in Zimbabwe have access to improved water sources, while the rest especially in rural areas drink water from unprotected sources (FSIN and GNAFC, 2023). As a result, Zimbabwe is currently struggling to contain a cholera outbreak which reportedly started in February 2023 and whose counting toll is more than 23905 and 525 cumulative cholera cases and deaths, respectively (Olatunji *et al.*, 2023; ReliefWeb, 2024). Approximately a third (33.7%) of households in Zimbabwe use grid electricity, about 28.3% use local off-grid electricity, 38% lack access to all forms of electricity, while 61-90% rely on biomass (mainly firewood especially in the rural areas) for cooking (UNEP, 2017; ZimStat, 2023a). Just like in neighbouring South Africa and other countries in southern Africa, the power utility company (Zimbabwe Electricity Supply Authority, ZESA) manages the frequent electricity deficit by electricity load shedding (imposed power blackouts) whose cycles are reported to be sometimes as high as 18 hours (2019) to 20 hours (2022) daily, with some citizens reportedly getting electricity only from midnight to 4 am (GoZ, 2012b; The Citizen, 2022). In 2022, Zimbabwean

households whose food consumption patterns were borderline to poor were 65% and 21%, respectively, while moderate to severe hunger was 13-15%, and reported food insecurity was 29-31% (ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC and FNC, 2023b). Currently due to the El Niño weather phenomenon, Zimbabwe is in a nationwide State of Disaster Drought (like Malawi and Zambia) which needs approximately US$2 billion for food relief (Moyo, 2024a; Murwira, 2024). With Zimbabwe facing major challenges and showing decreasing trends in achieving WEF-related SDGs, among others, there is need for revamped efforts to close the gaps between current achievements and desired short-, medium- and long-term targets of WEF security as promised in the national aspirations.

The security of the interconnected WEF resources amidst multiple drivers of demand and supply depends on, among others, the way in which the resources are managed in response to demand, whether under normalcy or scarcity. Sectoral planning leads to trade-offs and amplifies WEF resource use competition, inefficiency, and insecurity (Mpandeli *et al.*, 2018; Mabhaudhi *et al.*, 2023). The Southern African Development Community (SADC) echoes that sectoral approaches are denying the region of cost-effective mechanisms to implement programmes, while the Government of Zimbabwe partly blames the silo mentality and lack of an integrated planning approach for the decline in its infrastructure, the slow pace in renewable energy development, and suboptimal implementation of government programmes (SADC, 2016; GoZ, 2019; GoZ, 2020b; GoZ, 2020c). Thus perpetuating "business as usual" approaches to WEF resources management under changing climate and socioeconomic conditions will most likely intensify resources competition, degradation and depletion: it is no longer an option if society is to secure WEF resources for all today and in the future (FAO, 2017). On the other hand, integrated approaches such as the water-energy-food (WEF) nexus seek to understand the interconnections between WEF resources, optimize the synergies, minimise the trade-offs, and harmonize actions to enhance resource security for economically efficient, socially equitable and environmentally sustainable development (Mpandeli *et al.*, 2018; Naidoo *et al.*, 2021). Strategic and fundamental resources such as water, energy and food are inextricably and concomitantly interconnected in a water-energy-food (WEF) nexus such that actions in one sector influence the other sectors, either synergistically or adversely in the hydrological, biological, social, and technological realms (Hoff, 2011; Beekma *et al.*, 2021).

Zimbabwe has witnessed its fair share of WEF nexus work including in policy dialogue (GWP-SA, 2022) and research. The context of some of the previous WEF nexus research work in Zimbabwe was transformation of rural livelihoods and well-being (Mabhaudhi *et al.*, 2019),

scenario planning (Zambezi River Basin, ZRB) (Koundouri and Papadaki, 2020), land use change (ZRB) (Gomo *et al.*, 2018), and WEF potential of water infrastructure (Mujere and Chanza, 2022). Other studies focused on challenges to WEF nexus security and coping strategies (Jaka *et al.*, 2023), local urban sustainability and resilience (Chirisa and Bandauko, 2015), potential for resource recovery (water, energy, food and nutrients) from wastewater treatment, as well as impacts of the WEF adaptive strategies and their environmental implications (Gandidzanwa and Togo, 2022).

Although Zimbabwe was one of the early adopters of the water-centric Integrated Water Resources Management (IWRM) approach which it embedded in its water law and policy and uses to govern the water sector (GoZ, 2012b; Mabiza, 2013), none of the policy documents in the country explicitly mentions the WEF nexus approach. Progress in implementation of the IWRM approach in Zimbabwe was hampered by, among others, policy incoherence (e.g., water reforms vs. land reforms), multiple, disparate and discordant institutions involved in water resources management, as well as lack of a clear roadmap or methodological approach (e.g., catchment development master plan) to guide the integration and harmonization of institutions (Marimbe and Manzungu, 2003; Chereni, 2007; Saravanan *et al.*, 2009; Mehta *et al.*, 2016; Dirwai *et al.*, 2021). However, some key policies acknowledge and emphasize a key tenet of nexus approaches, that is, the importance of integrated planning for resources management through cross-sectoral coordination and cooperation between government departments, and these include the National Development Strategy 1 (NDS1, 2021-2025) (GoZ, 2020b), the National Renewable Energy Policy (2019) (GoZ, 2019), the National Water Policy (GoZ, 2012b), the National Energy Policy (GoZ, 2012a), and the Strategic Plan (2021-2025) (GoZ, 2020c). For example, in the National Energy Policy (GoZ, 2012a), the government pledges to develop an integrated energy plan, and integrate and harmonise implementation of the various national policies. Zimbabwe 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; GoZ, 2021; AU, 2023). However, WEF resource planning and management remains sectoral in Zimbabwe. Since districts and catchments are quintessential units for service delivery and water management in Zimbabwe, there is need for more WEF nexus studies at these sub-national scales to inform integrated evidence-based resource planning and decision-making (GoZ, 2012b).

At this juncture it is important to assess the state of the WEF nexus at sub-national scales and use the findings to inform the adoption and implementation of emerging resource management frameworks such as the WEF nexus. This study's research problem is the paucity of evidence of the WEF nexus that can inform implementation of the approach at sub-national scales such as catchments and districts in southern African countries, including Zimbabwe where some integrated approaches have been embraced and successfully embedded in some sectoral policies. The general aim of this research was to assess the state of implementation of the WEF nexus approach in Zimbabwe using a case study approach at sub-national scales, particularly at catchment (Mzingwane) and district (Umzingwane) level. It is hypothesised that, from a nexus perspective, the management of WEF resources is suboptimal at catchment and district levels, and there is need for intervention efforts that can improve the status quo. The research is envisaged to provide evidence on the sustainability of management of WEF resources, from a nexus perspective, that informs priority areas for intervention in catchments and districts such as Mzingwane and Umzingwane, respectively.

5.2 Materials and Methods

To assess the WEF nexus in Mzingwane Catchment and Umzingwane District in Zimbabwe, this study used mixed methods including WEF nexus modelling with the geospatial web-based integrative water-energy-food nexus analytical modelling tool (iWEF) with inputs from key expert stakeholders, and supported by observations, databases, and literature. This study followed a flowchart like the one in Chapter 4 (see Chapter 4, sub-section 4.2, Figure 4.1).

5.2.1 Case study areas

Mzingwane Catchment and Umzingwane District were chosen as case studies because they are typical nexus theatres in Zimbabwe and southern Africa characterised by renewable energy development, dam construction, irrigation expansion and transboundary resources under water scarcity, growing populations, and climate change and variability (ZimStat, 2023a). For example, the Government of Zimbabwe recently signed a Memorandum of Understanding (14 March 2024) with the Government of South Africa, for the former to sell 15 Mm^3 of treated water monthly (41 ML/day) to the latter by 2026. The water will originate from Zhovhe Dam, be treated at Beitbridge Water Treatment Works, and transferred across the border to Musina town (GoSA, 2024). Thus, it is necessary to do baseline WEF nexus studies that can be used to

inform potential synergies and trade-offs that may be accrued from implementing ongoing and planned WEF-related developments, for the management of risks to the triple bottom line: people (e.g., WEF security, livelihoods), prosperity, and planet.

5.2.1.1 Mzingwane Catchment (Zimbabwe) (Appendix G and H)

5.2.1.1.1 Basin characteristics and drainage systems

Mzingwane Catchment is in the northern parts of Limpopo River Basin and south-western parts of Zimbabwe, and located between 19.8° and 22.4° S and 27.7° and 32.0° E. The catchment covers an area of approximately 63000 km^2 and consists of four sub-catchments namely Shashe (20140 km^2), Upper Mzingwane (2138 km^2), Lower Mzingwane (26936 km^2), and Mwenezi (13786 km^2) (LBPTC, 2010a; Sibanda *et al.*, 2020; Maviza *et al.*, 2022) (Figure 5.1). Mzingwane Catchment has five major rivers (Shashe, Umzingwane, Mwenezi, Bubi and Marico) that feed into the Limpopo River (LIMCOM *et al.*, 2017; Sibanda *et al.*, 2020).

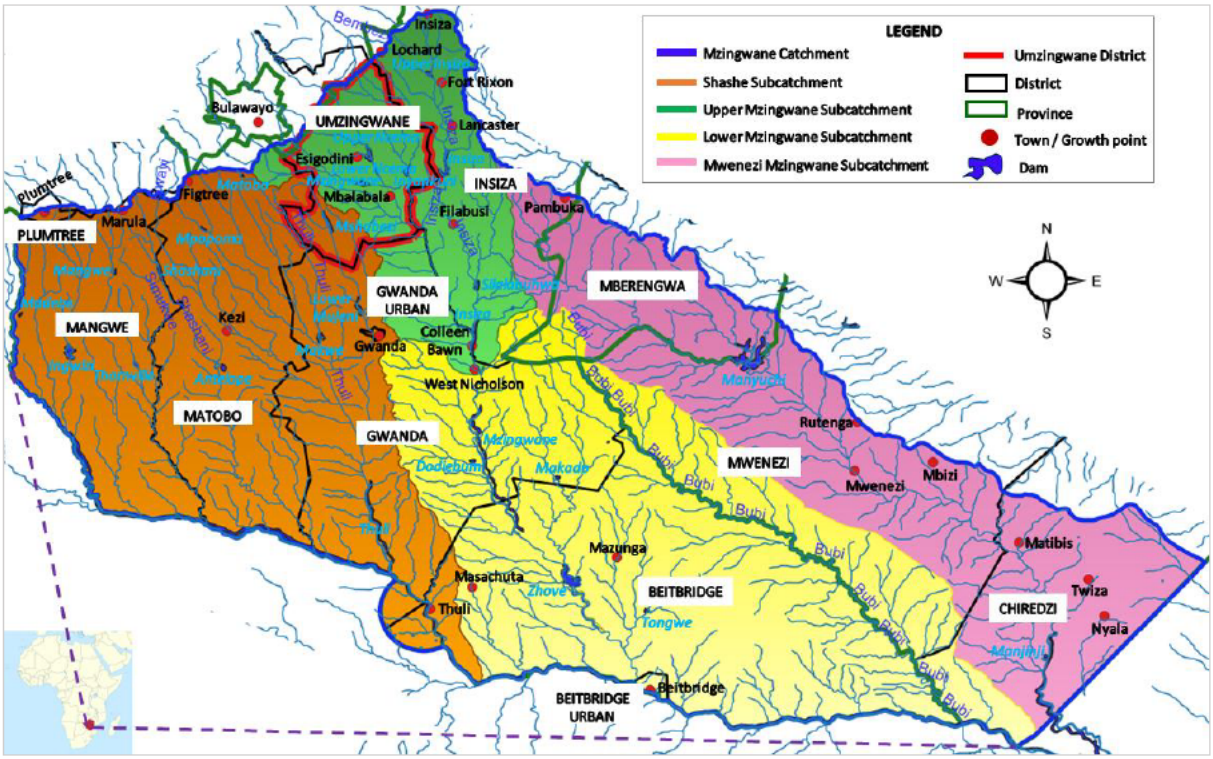


Figure 5.1: The location of **Mzingwane Catchment**, its four sub-catchments (Shashe, Upper Mzingwane, Lower Mzingwane, Mwenezi), and its overlapping provinces and districts including **Umzingwane District** (bounded in red) in Zimbabwe (Love *et al.*, 2005; OCHA, n.d.)

5.2.1.1.2 Demography

Mzingwane Catchment is home to 874000 people and 214645 households (ZimStat, 2023b). The catchment straddles on parts of three provinces (Matabeleland South, Masvingo and Midlands), nine rural districts (Beitbridge Rural, Gwanda Rural, Mangwe, Umzingwane, Matobo, Insiza, Chiredzi Rural, Mwenezi, Mberengwa) and three urban districts (Beitbridge Urban, Gwanda Urban, Plumtree), and 197 wards (ZimStat, 2023b). A household has an average of 4 people and the population density per square kilometre ranges between 14 (Matabeleland South), through 29 (Masvingo) and 37 (Midlands), while the total population is projected to reach 889293 and 904924 people by 2030 and 2040, respectively (LIMCOM *et al.*, 2017). Approximately 85% of the total population in Mzingwane Catchment lives in rural areas (Mabiza *et al.*, 2007; LIMCOM *et al.*, 2017). Beitbridge is the economic hub, major urban and industrial centre in the catchment and is the main economic gateway between South Africa and Southern and East Africa.

5.2.1.1.3 Climate

Mzingwane Catchment is arid to semi-arid, receives irregular, erratic, and spatially and temporarily variable and deficient precipitation most of which is lost to high rates of evapotranspiration (UNEP, 2010; LIMCOM, 2011; Sibanda *et al.*, 2020). The catchment is situated mainly in revised agro-ecological zones (AEZs) IV, Va and Vb, with a small portion in AEZ III, and thus it 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; GoZ, 2022j). 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). Rainfall in Mzingwane Catchment decreases from north to south while the mean annual rainfall of 635 mm/yr is less than the global average annual rainfall (860 mm/yr). The maximum temperature increases from north to south with the average daily maximum temperature ranging from 22 °C to 34 °C, while the average minimum temperature ranges from 5 °C to 22 °C (Love *et al.*, 2010; LIMCOM, 2011; Manatsa *et al.*, 2020). Driven by low humidity and high temperatures, evaporation and evapotranspiration

(1592 mm/yr) are high and make dryland subsistence agriculture extremely challenging in the catchment (LIMCOM, 2011; Zhu and Ringler, 2012).

5.2.1.1.4 Water availability and demand

The total storage in water reservoirs in Mzingwane Catchment is 1210 Mm^3 (Murwira and Yachan, 2007; LIMCOM *et al.*, 2017). 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). The catchment supplies water (60 Mm^3/annum) to Bulawayo City which is located on the watershed of Umzingwane and Gwayi catchments (Mkandla *et al.*, 2005; LIMCOM *et al.*, 2017). High poverty in the catchment is driven by limited livelihood options available to most of the population, and the unfavourable climate, especially low rainfalls and high temperatures, which complicate the main livelihood source for most households, i.e., agriculture (GoZ, 2022f). However, national water resources management interests and priorities in Mzingwane Catchment are mainly irrigation expansion to at least 4000 hectare (from the current 3000 ha and a potential of 10 900 ha) by 2025, irrigation rehabilitation and modernisation, agricultural development, and expanding water storage (CSIR, 2003; FAO, 2004; Murwira and Yachan, 2007; LBPTC, 2010b; LIMCOM *et al.*, 2017; Dickens *et al.*, 2020; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). However, water is and will likely remain a major limitation to development in the Mzingwane Catchment (LIMCOM, 2011).

5.2.1.2 Umzingwane District (Zimbabwe) (Appendix G and H)

5.2.1.2.1 District characteristics and demographics

Umzingwane District (2797 km^2) is in the south-western part of Zimbabwe, and the northern parts of the Matabeleland South Province and Mzingwane Catchment (bounded in red colour in Figure 5.1). The district shares boundaries with Bulawayo City to the north, Bulilima District to the west, Matobo District and Gwanda Districts to the south, and Insiza District to the east (GoZ, 2022l). Umzingwane District is completely enclosed within Mzingwane Catchment,

while major and minor parts of the district are in the Upper Mzingwane and Shashe sub-catchments, respectively (Figure 5.1). The district is mainly rural, with 20 administrative wards and a total population of 17958 households and 71860 people (ZimStat, 2023b). Umzingwane District is located in revised agro-ecological zones (AEZs) III (northmost part) and IV (mainly) (Manatsa *et al.*, 2020; GoZ, 2022j).

5.2.1.2.2 Climate and water

According to characteristics of the revised AEZs, rainfall in Umzingwane District ranges from 450 mm/yr to 800 mm/yr and decreases from north to south, while maximum temperatures and evapotranspiration increase in the same direction (Manatsa *et al.*, 2020; GoZ, 2022l). The annual mean minimum and maximum temperatures are 5°C and 30°C, respectively, while evapotranspiration ranges between 1800 mm/yr to 2000 mm/yr (Maviza and Ahmed, 2020). According to Manatsa *et al.* (2020) and compared to its host Mzingwane Catchment, Umzingwane District receives a slightly higher bounded range of annual rainfall with a higher probability (60% – 80%) of exceeding 500 mm/yr of rainfall, and experiences slightly lower maximum temperatures. Umzingwane District experiences frequent seasonal droughts and severe dry spells during the rainy season which can lead to temporary and permanent crop wilting (Maviza *et al.*, 2022). Thus, the district is more suitable for semi extensive farming systems based on livestock, resistant fodder crops, forestry, wildlife and tourism (GoZ, 2022l). Umzingwane District hosts eight irrigation schemes (Zimbili, Duncal, Mzinyathini, Kumbudzi, Portbury [1 and 2], Mbilambowe, and Khomani), numerous community gardens, and five major dams namely Mtshabezi, Mzingwnane, Lower Ncema, Upper Ncema, and Inyankuni (GoZ, 2022l).

5.2.2 The geospatial web-based integrative analytical tool for the water-energy-food nexus

For analysing the status of WEF nexus in Mzingwane Catchment and Umzingwane District, this study applied the geospatial web-based integrative water-energy-food nexus analytical modelling tool (iWEF, https://www.iwef.app/). iWEF was initially developed by Mabhaudhi *et al.* (2019) and Nhamo *et al.* (2020) and further improved and enhanced by Taguta *et al.* (2023). The six indicators in iWEF, calculated per annum, are presented in Table 5.1.

Table 5.1: The six indicators in the iWEF model (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020; 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

Details on the iWEF model is available in Chapter 3 and in the background paper by Taguta *et al.* (2023), and more information on how the model was applied in this current case study is presented in Section 4.2.2 of Chapter 4.

5.2.3 Data collection

5.2.3.1 Indicator pairwise judgements as qualitative WEF nexus data

The data for iWEF modelling was collected and handled following the procedures outlined in Section 4.2.3.1 of Chapter 4. The initial pairwise comparison matrices (PCMs) of WEF-related indicators (Table 5.1) from key expert stakeholders for Mzingwane Catchment and Umzingwane District were inconsistent (consistency ratio, $CR > 0.1$) with CR values of 15.6% and 28.1%, respectively (Mu and Pereyra-Rojas, 2017). The same stakeholders were re-engaged iteratively to systematically revise some of their outlier judgements as guided by the AHP Priority Calculator (https://bpmsg.com/ahp/ahp-calc.php) (Goepel, 2022). The iterative revision of outlier judgements yielded finalised consistent PCMs (Appendix I) with acceptable

consistency ratio (CR) values for Mzingwane Catchment (8.6%) and Umzingwane District (2.3%) (Table 5.2).

The shapefiles for delineating the boundaries of Mzingwane Catchment and Umzingwane District in the iWEF model were obtained from Zimbabwe National Water Authority (ZINWA) (ZINWA and Dabane Trust, 2022) and the Humanitarian Data Exchange by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (OCHA, n.d.).

5.2.3.2 Quantitative WEF nexus data

A variety of sources and existing open data were leveraged to synthesize and enhance knowledge of the WEF nexus from otherwise isolated domains (Table 5.1) (Sowby and Dicataldo, 2022). The quantitative data for WEF nexus security indicators to support interpretation of the results from iWEF modelling were obtained or derived from established databases, archives and publications such as those from statistical agencies (Zimbabwe National Statistics Agency, ZimStat), government publications (reports, policies, strategies, census, surveys), and literature (Love *et al.*, 2005; LBPTC, 2010a; LIMCOM *et al.*, 2017; ZimStat, 2019; Dickens *et al.*, 2020; ZERA, 2021; ZERA, 2022; ZimStat, 2022; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). Out of the six indicators (water availability, water productivity, energy accessibility, energy productivity, food self-sufficiency, cereal [or crop] productivity), those that were not available in databases and reports were estimated, based on available data using the definitions and relationships in Table 5.1 (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020; Taguta *et al.*, 2023). For example, indicators for productivity (economy-wide) of water and energy at catchment and district scale were estimated with population aggregated (catchment) or disaggregated provincial Gross Domestic Product (GDP) and GDP per capita, and consumption of water and energy (LIMCOM *et al.*, 2017; Veritas, 2020; ZimStat, 2022). As in Aurecon (2013), wherein the catchment does not fully align with administrative boundaries, the catchment populations were estimated by proportionally distributing the published population of the smallest unit (province or district or ward) from the census figures over the part of the unit that fall in the catchment. For the target WEF security indicators, the latest comprehensive dataset for the selected sub-national case studies in Zimbabwe was for 2021/22 (Table 5.2).

5.3 Results and Discussion

5.3.1 Status of WEF nexus in Mzingwane Catchment and Umzingwane District

5.3.1.1 Quantitative values of WEF security indicators in Mzingwane Catchment and Umzingwane District

The quantitative values of the six indicators of security of WEF sectors for Mzingwane Catchment and Umzingwane District obtained from established databases and published literature are presented in Table 5.2, together with the quantitative results from the iWEF modelling exercises. According to the sustainability scale in Table 5.2, it is apparent that the security and sustainability of WEF resources in Mzingwane Catchment and Umzingwane District is suboptimal (Table 5.2). These results are the subjects of discussion and minor comparison in the succeeding sub-sections.

Table 5.2: Overview of the WEF nexus indicators for selected case studies in Mzingwane Catchment and Umzingwane District in Zimbabwe for the period 2021/2022

WEF nexus pillar	Indicator and units	Case study		Scaled categories of performance for WEF related indicators[10]			
		Mzingwane Catchment	Umzingwane District	Unsustainable	Marginally Sustainable	Moderately Sustainable	Highly Sustainable
Water	Water availability (WA, m^3 /cap/yr)[1,2,3]	~1021	~1130	WA < 1700	1700 ≤ *WA* ≤ 6000	6000 < *WA* ≤ 15000	WA > 15000
	Water productivity (WP, \$/m^3)[1,2,3,4,5]	2.00	4.00	WP < 10	10 ≤ *WP* ≤ 20	20 < *WP* ≤ 100	WP > 100
Energy	Energy accessibility (EA, %)[2,3,5,7]	21.5	19.0	EA < 20	20 ≤ *EA* ≤ 50	50 < *EA* < 90	90 ≤ *EA* ≤ 100
	Energy productivity (EP, \$GDP/MJ)[2,3,4,5,7]	0.09	0.07	EP < 0.11	0.11 ≤ *EP* < 0.2	0.2 ≤ *EP* ≤ 0.33	EP > 0.33
Food	Food self-sufficiency (FSF, %)[6]	87.9	93	FSS < 70	70 ≤ *FSF* ≤ 85	85 < *FSF* ≤ 95	FSS > 95
	Crop productivity (CP, kg/ha)[5,6,8]	302.5	833.3	CP < 500	500 < *CP* ≤ 2000	2000 < *CP* ≤ 4000	CP > 4 000
WEF	Consistency ratio (CR, %)[9,10]	8.6	2.3	>10% is considered unsatisfactory			
	Integrated WEF nexus composite index (*i*)[9,10]	0.189	0.194	0.048 ≤ *i* < 0.107	0.108 ≤ *i* < 0.167	0.168 ≤ *i* < 0.226	0.227 ≤ *i* ≤ 0.286

(Sources: Zimbabwe National Water Authority – ZINWA (1); Limpopo Basin Permanent Technical Committee – LBPTC (2); Limpopo Watercourse Commission – LIMCOM (3); Government of Zimbabwe (4); Zimbabwe National Statistics Agency – ZimStat (5); Food and Nutrition Council – FNC and Zimbabwe Vulnerability Assessment Committee (ZimVAC) (6); Zimbabwe Power Company – ZPC, Zimbabwe Electricity Supply Authority (ZESA) and Zimbabwe Energy Regulatory Authority (ZERA) (7); Department of Agricultural Technical and Extension Services (AGRITEX) (8); Key expert stakeholders and iWEF model (9); (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020; Taguta *et al.*, 2023) *(10)).*

5.3.1.2 The iWEF perspective in based on perception of key expert stakeholders in Mzingwane Catchment and Umzingwane District in Zimbabwe

The results from iWEF modelling of PCMs (Appendix I) from stakeholders in Mzingwane Catchment and Umzingwane District are graphically presented in Figure 5.2 (Table 5.2).

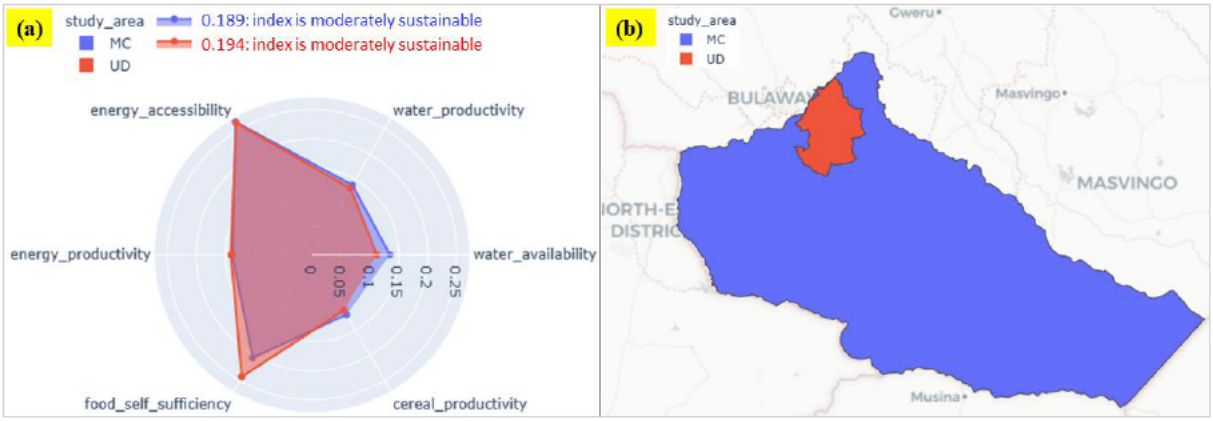


Figure 5.2: (a) Quantitative and graphical representation, and (b) spatial visualisation of the WEF nexus in Mzingwane Catchment (MC) and Umzingwane District (UD) in Zimbabwe *(colour codes in the map are for distinction and identification; all normalised indices of the six indicators use the same scale in the radar chart)*

5.3.1.2.1 Mzingwane Catchment (Zimbabwe)

With an iWEF 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 in Mzingwane Catchment is moderately sustainable, with a wide gap that needs improvement (Table 5.2, Appendix I, Figure 5.2). The irregular shape of the centrepiece in the spider diagram is evidence of unbalanced management of the WEF resources in the catchment. At sector level, the energy sector outperforms the food sector followed by the water sector. At indicator level, food self-sufficiency and energy accessibility are faring well compared to other indicators, followed by energy productivity, cereal productivity, water availability and water productivity. Several challenges to WEF security were reported by key expert stakeholders, in literature and noted by observation in the case study areas (Figure 5.3). These are discussed per sector in the succeeding sub-sections.

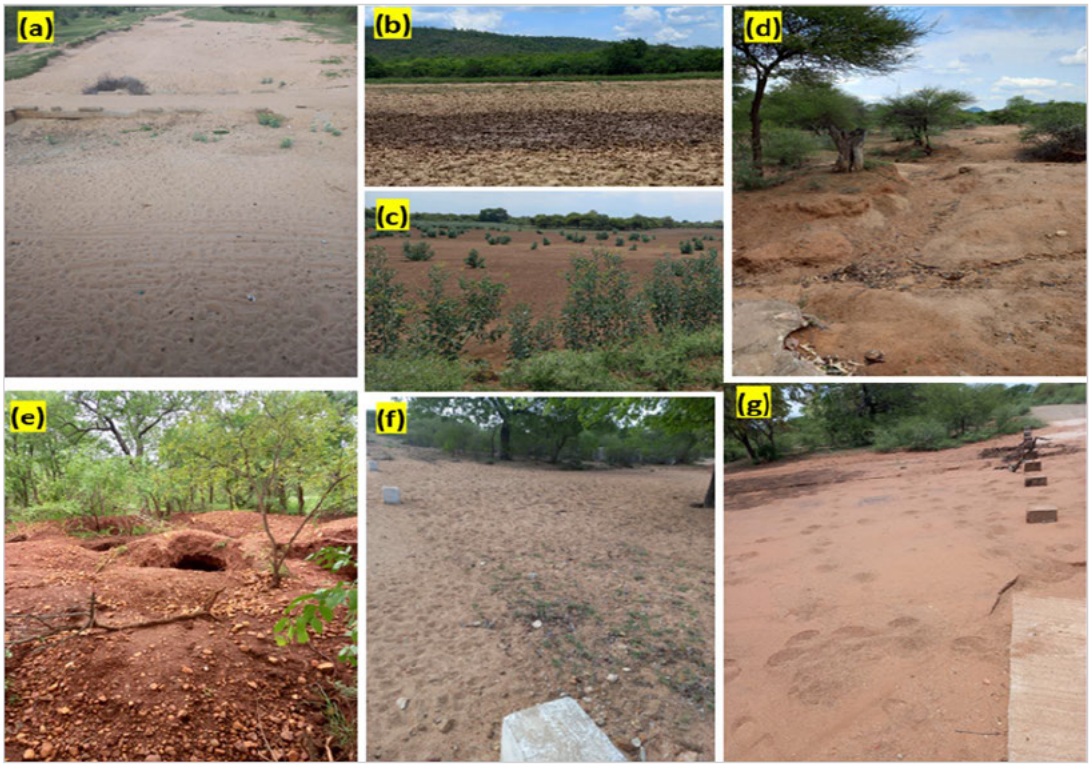


Figure 5.3: Dry river beds (a) at Pendi, and dams in (b) Esibomvu, and (c) Mashaba; (d) land degradation at Mashaba; (e) artisinal mining in Gwanda; and siltation in (f) Tuli and (g) Mashaba

(a) Water security

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). The region is water stressed and is challenged with water scarcity as evidenced by dried-up river beds and dams (Figures 5.3a-c). Mzingwane Catchment is water scarce and stressed (below 1700 m^3/capita per year) and will likely experience chronic water scarcity (below 1000 m^3/capita per year) in 2030 (Falkenmark *et al.*, 1989; Alemaw *et al.*, 2008; Dickens *et al.*, 2020). The continuous decommissioning of large dams (e.g., Umzingwane Dam, 2023) in Mzingwane Catchment is undermining water security in the catchment as Upper Ncema and Lower Ncema will likely be decommissioned later this year (2024) due to depletion (LIMCOM *et al.*, 2017; UN-Habitat and Tongji University, 2022). As of the 6th of May 2024, water levels were low in major dams in Mzingwane Catchment including Inyankuni Dam (20.2%), Upper Ncema Dam (15.9%), Mzingwane Dam (2.9%), Lower Ncema Dam (4.3%), and Upper Insiza Dam (11. 5%) (ZINWA, 2024). Meanwhile, small dams in Mzingwane Catchment are mostly

in poor physical condition mainly due to lack of resources for repair and maintenance (Mufute *et al.*, 2008). The situation is exacerbated by land degradation including soil erosion (Figure 5.3d), inter alia, due to deforestation, over grazing and poor soil management practices (GoZ, 2022f). Land degradation is worsened by demographic pressures, intensive land use, high climate variability, increasing aridity, floods, frequent droughts, infestation by invasive alien plants, surface and groundwater abstraction, damming of rivers, uncontrolled veld fires and pollution of water from mining activities and commercial agriculture (LIMCOM, 2011; LIMCOM *et al.*, 2017). Wetlands are exploited for food production. Water challenges include inadequacy of treatment chemicals and equipment (e.g., pumps) due to high costs and unavailability of foreign currency (Remigios and Never, 2010; Musemwa, 2021; Brooke and Fenner, 2023). Generally, the Matabeleland South region lacks groundwater resources due to deep water tables. Due to limited livelihood options and the promise of valuable minerals in the ground, the region suffers from artisanal or illegal mining some of which is done on agricultural land and attracts illegal miners from other regions across Zimbabwe (Figure 5.3e). The poor land management practices accelerate natural processes and result in siltation of rivers and dams and thus compromising water security, agricultural water availability and food production. Similarly, poor land management practices and illegal mining cause water pollution by chemicals such as mercury and cyanide which are harmful to human health (Masere and Sibanda; Dalu *et al.*, 2017; Makwerere *et al.*, 2018; Mambrey *et al.*, 2020). According to some key expert stakeholders from ZINWA and irrigation, some water users such as farmers tend to use water illegally by irrigating without water permits and deliberately extracting more than the allocated amount of water.

Water security is undermined by compromised water sources (48%) due to siltation (35.1%) (Figures 5.3f-g), breached or broken dam walls (6.2%) and leaking (Figure 5.4a) (GoZ, 2022b; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h).

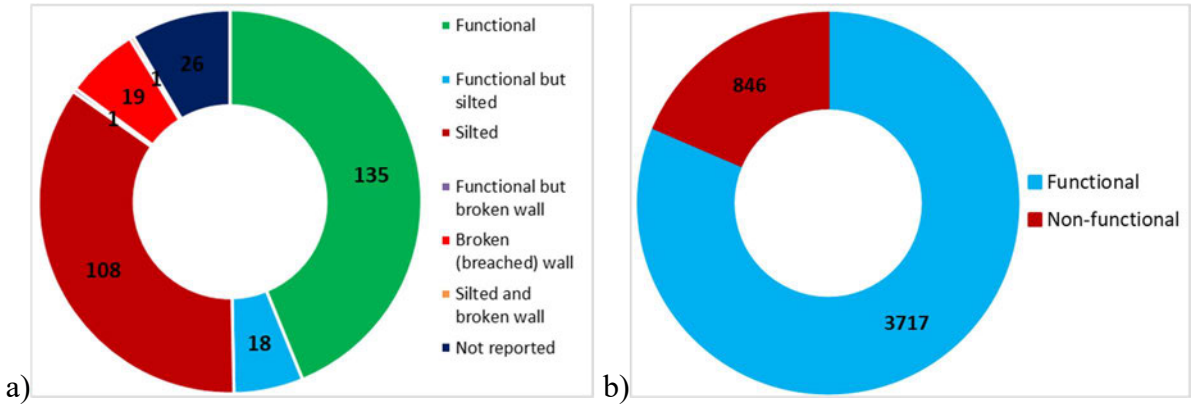


Figure 5.4: Functional status of (a) all water sources, and (b) boreholes in Mzingwane Catchment. (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022e; GoZ, 2022k; GoZ, 2022l)

For example, 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 (Figure 5.4b) (GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022l). Groundwater resources in Mzingwane Catchment are not very productive, with many of the domestic wells and boreholes supplying individual households and small communities drying up before the end of the dry season (LIMCOM, 2011). The current status of irrigation technology is dominated by flood irrigation systems which are inefficient in water use, undermine water productivity, and drive water insecurity (Figure 5.5).

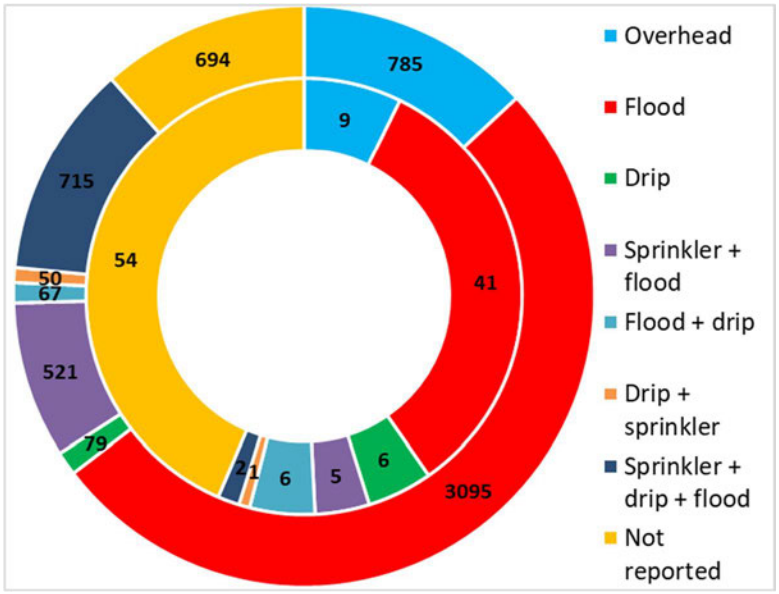


Figure 5.5: Irrigation technologies in existing irrigation schemes. *(Inner core = by number; Outer core = by area, ha)*. (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022e; GoZ, 2022k; GoZ, 2022l)

The planned sale of treated water from Beitbridge Water Treatment Works to Musina town will leave Zhovhe Dam in Mzingwane Catchment short of 15 Mm^3 (41 ML/day) and potentially exacerbate water insecurity in the catchment (GoSA, 2024).

(b) Energy security

In the energy sector, connection to the grid (national and mini) of electricity is generally low (22%) although the situation is worse in rural areas (19%) than urban areas (47%) (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e; ZimStat, 2023a). Rural areas in southern African countries including Zimbabwe usually lag behind urban areas in economic development, provision of basic services, and access to resources (Mabhaudhi *et al.*, 2019; ZimStat, 2023a). The same applies to households that use clean energy for cooking, lighting and heating including electricity, solar, biogas, liquefied petroleum gas (LP), alcohol/ethanol (gel). 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, 2022a; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). The use of dirty and polluting fuels like firewood cause air

pollution which induce ill health and lead to between 0.8 - 1.1 million deaths per year globally (Craig *et al.*, 2022; SE4ALL, 2023). The cutting down of trees for firewood is a major cause of deforestation and land degradation in Zimbabwe wherein about 0.1 to 0.3 million hectares of indigenous forests are lost annually due to indiscriminate cutting down of trees and veld fires (Mubaiwa, 2021). Approximately 85% of this wood (9 to 11 million tons) is firewood that is utilised for domestic cooking and heating by households (Moyo, 2019). With the current low rates of electrification and satisfaction of energy demand especially electricity in Zimbabwe, trade-offs exist between both the the level of electrification and reliable electricity supply and conservation forests in the environment. Despite their relatively high connectivity to electricity networks, urban people suffer acute energy insecurity due to electricity load shedding which dates as far as the 2000s. Electricity supply is insufficient to meet demand due to suppressed and inadequate generation and this has prompted the supply authority (Zimbabwe Electricity Supply Authority, ZESA) to implement long periods of electricity load shedding (GoZ, 2012b). There is a slow embrace and adoption of renewable energy especially in rural areas. Connected households waste electrical energy through use of high wattage incandescent lights. Inefficiency in water use in the dominant flood irrigation systems (Figure 5.5) undermines energy productivity in Mzingwane Catchment.

(c) Food security

Cereal productivity performed relatively poorly despite the (i) increase in area under small-scale irrigation in drier regions during the period 2013 to 2018, (ii) stable cereal prices, (iii) introduction of input support scheme through the special maize and wheat programme (known as “command agriculture”), and (iv) increase in the area under climate proofed technologies and initiatives (Pfumvudza / Intwasa). Despite these favourable interventions and conditions, maize production was still suboptimal due to poor rainfalls and dry spells (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; AU, 2023; FSIN and GNAFC, 2023). The average maize yield in Mzingwane Catchment has always been lower than the average of 3600 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 a major part of the irrigated area (approximately 68%) is partly functional and not functional (Figure 5.6a).

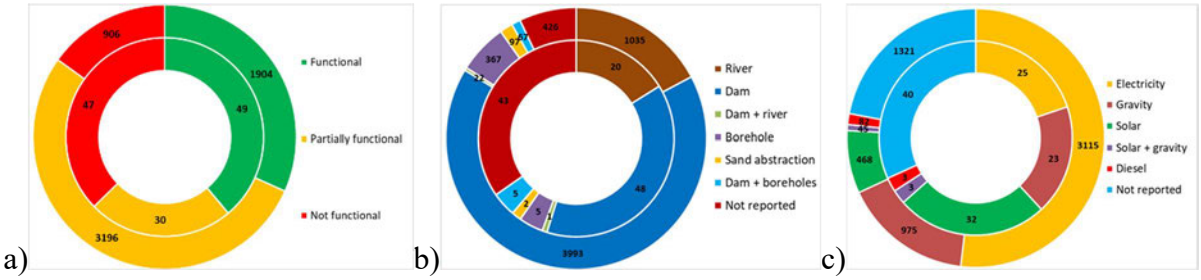


Figure 5.6: a) Functional status of existing irrigation schemes, and sources of (b) water and (c) energy for irrigation schemes in Mzingwane Catchment. *(Inner core = by number; Outer core = by area, ha)*. (GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022e; GoZ, 2022k; GoZ, 2022l)

Partly- and non-functional irrigation schemes are undermined by challenges related to inadequate infrastructure (water sources, pumps, fencing, inputs, capital, roads), insufficient resources (water supply, electricity power cuts), poor operation and maintenance (water efficiency, clogged water pipes, water leakages, dilapidated electricity infrastructure, vandalism), wildlife-human conflicts, lack of knowledge, management and governance (agronomic, resistance to innovation, poor extension services, farmer organisation), unfavourable land tenure system, unfavourable markets and prices (inputs, producer), old age of the plot holders, economic (unaffordable electricity and water bills), pests and disease outbreaks, and climate-related limitations (poor rainfall distribution, droughts/dry spells incidences, erratic rains, flooding, hailstorms, strong high winds, deep groundwater tables, waterlogging) (Dickens *et al.*, 2020; GoZ, 2022b; GoZ, 2022d; GoZ, 2022i; GoZ, 2022e; GoZ, 2022k; GoZ, 2022l; ZimVAC and FNC, 2022d). A majority of irrigation schemes in Mzingwane Catchment depend on dams and rivers (84.1% by area) and grid electricity (52%) as the sources of water and energy, respectively (Figures 5.6b-c) and this exposes agriculture and food security to the risks of intermittent supplies of water and electricity.

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 food assistance from government and development partners including grain, porridge and pulse meals (World Bank, 2019; ZimStat, 2019; Muhoyi and Mbonigaba, 2022; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b). Some households receive remittances from the diaspora (e.g., South Africa or Botswana) and urban areas in form of mobile transfers of cash and food, the former which is also used to buy food among others (Ndlovu *et al.*, 2020; Sithole *et al.*, 2023; Moyo, 2024b). In the food, agriculture and water sectors, inflation, instability of the local currency and lack of funding inhibits the resuscitation

of irrigation schemes and boreholes. The COVID-19 restrictions undermined food security (GoZ, 2022j). Miners invade agricultural land, and this has caused some conflicts with farmers. After mining illegally for gold, sand, quarry stone and clay, the miners often leave open pits wherein animals (livestock) fall and die (LIMCOM, 2011; GoZ, 2022b; GoZ, 2022f). Other challenges include livestock theft and unavailability of labour force in agriculture as youth embark into mining or migrate to South Africa and other neighbouring countries in search of economic opportunities. There is a general prevalence of poor agricultural practices (e.g., streambank cultivation) and absence of soil and water conservation measures such as contours (GoZ, 2022f). Coping strategies by poor rural households during lean times include consumption and sale of wild fruits and insects, as well as exchanging casual labour (e.g., weeding) for cereals (GoZ, 2022f; Trisos *et al.*, 2022; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e).

5.3.1.2.2 Umzingwane District (Zimbabwe)

With an iWEF integrated WEF nexus composite index of 0.194 (from a maximum of 0.286 (Taguta *et al.*, 2023)) calculated from stakeholder-based pairwise comparison matrices (PCMs) of the relative performance of six indicators in Umzingwane District, it is evident that the management of WEF resources is moderately sustainable, with a wide gap that needs improvement (Table 5.2, Appendix I, Figure 5.2). The irregular shape of the centrepiece in the spider diagram is evidence of unbalanced management of the WEF resources in Umzingwane District. At sector level, the energy sector outperforms the food sector followed by the water sector. At indicator level, food self-sufficiency and energy accessibility are faring well compared to other indicators, followed by energy productivity, cereal productivity, water availability and water productivity. The suboptimal performances in the WEF nexus and related sectors can be attributed to several factors raised by key experts, observed on the ground and reported in literature, as discussed in the succeeding sub-sections.

(a) Water security

Similar to its host catchment (Mzingwane), Umzingwane District is water stressed and will likely experience chronic water scarcity (below 1000 m^3/capita per year) in 2025 as water availability per person will decrease (Falkenmark *et al.*, 1989; Alemaw *et al.*, 2008; Dickens *et al.*, 2020). Bottlenecks to water security in Umzingwane District include low rates of household connection to the national and council water grid since the district is mainly rural.

Approximately 65% of the district population have access to basic water services, while the rest have access to limited water services (19%), unimproved water services (13%), and surface water (4%) which they treat mainly by boiling, adding bleach or chlorine, and letting it stand and settle (ZimVAC and FNC, 2022d). The dependence of Umzingwane District on the Bulawayo water supply system is risky since the district is last priority such that they usually fail to meet their monthly supply targets for the Umzingwane District, for example by an average of 7% in 2022. Stumbling blocks to water security include insufficient water infrastructure and water inefficiencies in irrigated agriculture (Figure 5.7).

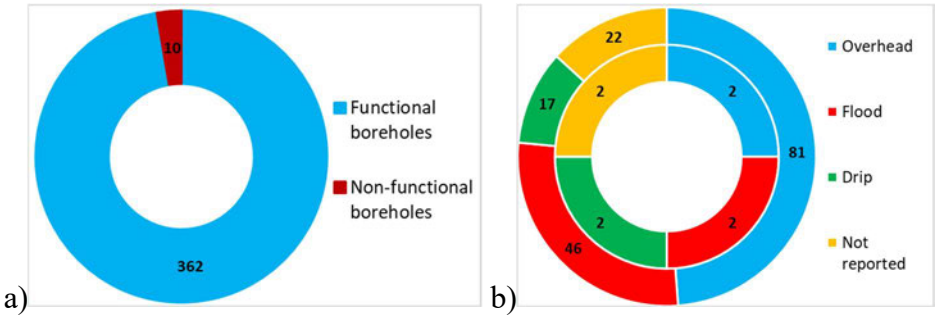


Figure 5.7: Status of (a) existing boreholes and (b) irrigation technology in irrigation schemes in Umzingwane District. *(Inner core = by number; Outer core = by area, ha). (GoZ, 2022l)*

With only 3% of all boreholes in Umzingwane District being non-functional, the issue of water insecurity is due to lack of adequate infrastructure (Figure 5.7a). However, some wards (4, 9, 10, 11) have rocky ground which present difficulties in drilling boreholes (GoZ, 2022l). Reasons for the non-functional boreholes include shortage of spare parts, and pipes failing to reach the water table due to either inadequate design or receding water tables (GoZ, 2022l). The continuous decommissioning of large dams (e.g., Umzingwane Dam, 2023) in Umzingwane District is undermining water security in the district as Upper Ncema and Lower Ncema will likely be decommissioned later this year (2024) due to depletion (LIMCOM *et al.*, 2017; UN-Habitat and Tongji University, 2022). As of the 6th of May 2024, water levels were low in major dams in Umzingwane District including Inyankuni Dam (20.2%), Upper Ncema Dam (15.9%), Mzingwane Dam (2.9%), and Lower Ncema Dam (4.3%) (ZINWA, 2024). The status of irrigation is potentially inefficient in water use, undermines water productivity and drives water insecurity (Figure 5.7b). For example, inefficient flood irrigation systems and relatively inefficient irrigation schemes constitute more than 75% of the irrigated area (GoZ, 2022l). According to key sector expert stakeholders, challenges to water security in

Umzingwane District include water scarcity, seasonality of water sources, and siltation of watercourses and water bodies (dams, weirs) due to illegal mining (gold panning - Wards 2, 4, 14, 15, 17, 18, 19). Water security is also affected by malfunctioning of infrastructure and equipment such as pumps, collapsed dam walls, water interruptions and incomplete installations.

(b) Energy security

Matabeleland South Province is home to Umzingwane District and the province has about 81% of households which are not connected to grid (national and local mini or off) electricity and hence are energy insecure (ZimVAC and FNC, 2022d; ZimStat, 2023a). Thus, majority of households in Umzingwane District largely rely on unclean solid polluting energy sources for cooking, lighting and heating including firewood, coal, charcoal, animal dung, paraffin lamps, grass or straws, candles and oil lamps (GoZ, 2022l). Deforestation is high in the district as the demand for wood resources for firewood, building materials, fuelwood business, and brick firing has drastically increased over the past several decades due to increased population pressure (GoZ, 2022l). Trends show decreases in areas with shrub and woody vegetation, with projections for future losses in dense woodland cover due to increased human activities in the area (Maviza and Ahmed, 2020). For those who are connected to the national grid of electricity (e.g., the per-urban Esigodini Growth Point), a major challenge is unreliability of supply caused by electricity load shedding and power cuts due to insufficient supply. Inefficiency in water use in flood irrigation systems undermines energy productivity in Umzingwane District.

(c) Food security

Food security was high (93%) probably due to the slight increase in adoption and production of small grains that are suited to the district's agroecology, such as sorghum, pearl millet, and the legumes including African pea and round nuts. This was achieved through the introduction of new farming technologies provoked by unfavourable climate and also through the support of non-governmental organisations (NGOs) (GoZ, 2022l). Some households in Umzingwane District were cushioned by external support such as remittances, food aid (in-kind), cash transfers, food subsidies, and social protection measures from the government and United Nations/NGOs (GoZ, 2022l; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b). However,

agriculture in Umzingwane District is limited by poor infrastructure (road networks, dam siltation), climatic extremes (droughts, dry spells, floods), lack of resources (water, energy, inputs, draft power, loan facilities due to collateral - the 99 year lease), economic challenges (poverty, high inflation, unemployment), overreliance of agriculture on erratic rains, lack of access to markets, crop and livestock diseases, and inadequate grazing area (GoZ, 2022l; Chisadza *et al.*, 2023a; Chisadza *et al.*, 2023b). Apparently, food security in Umzingwane District is closely interconnected to climate, especially the amount of rainfall received in the district, due to the predominant rainfed agriculture (Figure 5.8) (GoZ, 2022l).

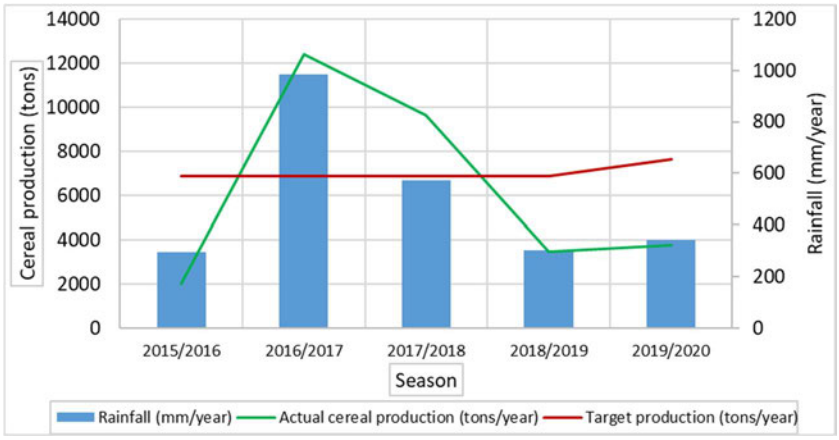


Figure 5.8: Trends of rainfall and total cereal production vs the target cereal production in Umzingwane District (GoZ, 2022l)

There was an approximately 43% reduction in production of cereals (maize and traditional grains) than the previous season 2020/2021 due to late rains that were poorly distributed with prolonged dry spells. On the other hand, the heavy rains from Tropical Storm Ana (January 2022) caused water logging and leaching of crop nutrients (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b). Food production was also affected by incidences of crop pests, and suboptimal functioning of some irrigation schemes (Figure 5.9a).

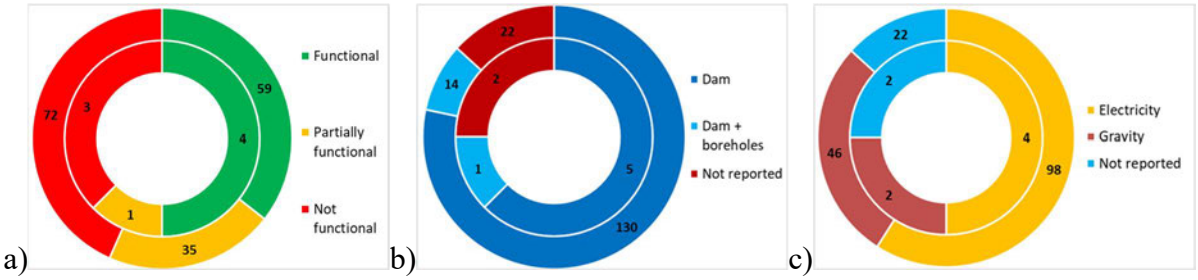


Figure 5.9: a) Functional status of existing irrigation schemes, and sources of (b) water and (c) energy for irrigation schemes in Umzingwane District. *(Inner core = by number; Outer core = by area, ha)*. Source: (GoZ, 2022l)

A majority (almost two-thirds) of the irrigation schemes in Umzingwane District are either partly functional or not functional at all (Figure 5.9a) (GoZ, 2022l). Irrigation schemes in the district largely depend on dams (78%) and electricity (59%) as the sources of water and energy, respectively (Figures 5.9b-c). This exposes agriculture and food security to the risks of intermittent supplies of water and electricity due to climate variability, competing demands, siltation (dams, rivers), and electricity load shedding and power cuts (GoZ, 2022l). Other bottlenecks to irrigated agriculture in the district include poor governance, and inadequate and dilapidated infrastructure (canals, pipes, fences, dams, electricity cables) (GoZ, 2022l). Food security is challenged by low soil fertility of the sandy soils (GoZ, 2022l). Mining takes priority over agriculture for access to land and some farmers are shifting from farming to mining. Miners prospect minerals in crop fields, while other farmers sell land to miners, and there are no mechanisms to restore mine degraded land (GoZ, 2022l). The illegal miners have a tendency of stealing in fields and gardens, while some livestock are lost when they fall into illegal mining pits. Pests and diseases for crops and livestock challenge agricultural production. Lack of capital inhibit investments in livestock production. The government-led conservation agriculture project is labour-intensive especially in hard soils. Other climate- and environment-related challenges include illegal hunting, and land degradation due to soil erosion, veld fires (July-October), invasive species (e.g., lantana camara), deforestation, overgrazing, and streambank and wetland cultivation (GoZ, 2022l).

5.3.1.2.3 The scale effect on WEF nexus

Although the purpose of this study was not to compare but to assess the state of the WEF nexus at the two different planning, water allocation and service delivery scales, i.e., catchment and district, some differences were noted in WEF nexus performances between Mzingwane

Catchment and Umzingwane District, both in indicators of WEF security and in the integrated WEF nexus composite index (Table 5.2, Figure 5.2). This can be attributed to the scale effect between Umzingwane District and Mzingwane Catchment, since the former is fully enclosed in the latter (Figure 5.1). Scale refers to the size of the analysis unit or the spatial extent of the study/implementation area, while the scale effect refers to the fact that different analysis results can be obtained when using coarser/finer analysis and measurement units (Sankey, 2015; Chen *et al.*, 2019; Ge *et al.*, 2019). In this case, the scale effect can arise from characteristic conditions including demography (population, population density, household size), agrometeorology (climate, hydrology, soils), 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 resource supply, demand and management. While Umzingwane District is just one district within the larger Mzingwane Catchment (Figure 5.1), the latter comprises Umzingwane District, eight other rural districts (Beitbridge Rural, Gwanda Rural, Mangwe, Matobo, Insiza, Chiredzi Rural, Mwenezi, Mberengwa) and three urban districts (Beitbridge Urban, Gwanda Urban, Plumtree). Accordingly, the WEF system in Mzingwane Catchment is an integration of the WEF system in Umzingwane District intertwined with WEF systems and subsystems in the other 11 districts. Thus, the state of the WEF nexus in Mzingwane Catchment is an aggregated combination of the state of WEF nexus in Umzingwane District and the other ten districts. To add, the two case studies are not exact replicas and thus cannot be expected to have exactly similar states of the WEF nexus.

A higher water availability in UD than MC is probably due to higher annual rainfalls and probability of exceeding 500 mm/yr, longer rainfall season, moderate maximum temperatures, and a high density / concentration of large dams (Mtshabezi, Mzingwnane, Lower Ncema, Upper Ncema, Inyankuni) than the latter (Manatsa *et al.*, 2020). However, 60 Mm^3/annum of water from all these dams and Insiza Dam is supplied to Bulawayo City (Aurecon, 2013; LIMCOM *et al.*, 2017; Dickens *et al.*, 2020). Umzingwane District has a higher WP than MC due to a higher proportion of water-efficient irrigation technologies in the former (at least 59%) than the latter (at most 48%), and the same argument can be extended to the observed state of energy productivity. Compared to Umzingwane District which is a rural underserved district, Mzingwane Catchment hosts three urban areas and has a higher energy accessibility than the former. Food self-sufficiency is lower in Mzingwane Catchment due to some districts that were relatively food insecure including Plumtree, Beitbridge (urban and rural) and Chiredzi rural (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC

and FNC, 2022c; ZimVAC and FNC, 2022e). On the other hand, UD was the third highest food self-sufficient district (93%) after Mangwe (97%) and Mberengwa (95.2%), while food self-sufficiency in the other districts ranged from 75% in Plumtree to 92% in Gwanda Urban (ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022b; ZimVAC and FNC, 2022a; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). The high cereal productivity in Umzingwane District than Mzingwane Catchment can be attributed to favourable agrometeorological conditions in the former, including higher annual rainfalls and probability of exceeding 500 mm/yr, a longer rainfall season, and moderate maximum temperatures than the latter (Manatsa *et al.*, 2020). Thus, WEF dynamics vary spatially and across scales/levels, and require localised analysis and context-specific interventions.

5.3.1.2.4 Summary

Findings from this study resonate with reports from other previous studies at various scales, especially on the suboptimal performance of sustainable resources management from a nexus perspective in Zimbabwe. Zimbabwe is located in the Southern African Development Community (SADC), a region wherein the management of WEF resources from a nexus perspective was reported to be marginally sustainable (Mabhaudhi *et al.*, 2019). In Harare City region and in place of government provided network services, communities are relying 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 nexus insecurity and 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 as far back as 1938 and 1949, respectively (Mkandla *et al.*, 2005; Chirisa and Bandauko, 2015). According to Gomo *et al.* (2018) between 1992 to 2015 in Zambezi River Basin (ZRB), tree cover declined by 4.6%, while cropland increased by 16% and urban areas doubled. Future resources demand and competition are expected to intensify in the future in Zimbabwe. For the ZRB wherein Zimbabwe is a riparian country, 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 to the supply chain in meeting those goals.

5.3.1.3 Improving the status of the WEF nexus in Mzingwane Catchment and Umzingwane District in Zimbabwe

There is unbalanced and moderately sustainable management of WEF resources in Mzingwane Catchment and Umzingwane District. The two case study areas need to manage their resources in ways that collectively improve the (i) performance of WEF security indicators (Table 5.2) and (ii) indices of performances for the WEF sectors (Appendix I and Figure 5.2), while ensuring the (iii) centrality of their centrepieces in iWEF sustainability polygons (Figure 5.2). Areas of prioritization can be apparently identified from a combination of findings in Table 5.2 and Figure 5.2. Apparently, in the two case studies, the indicators that would be given priority for improvement by interventions in Umzingwane District would be water availability, water productivity, energy productivity, and crop productivity (Table 5.2; Figure 5.2). Some interventions are already planned and ongoing to improve WEF security in Mzingwane Catchment and Umzingwane District (Figure 5.10).

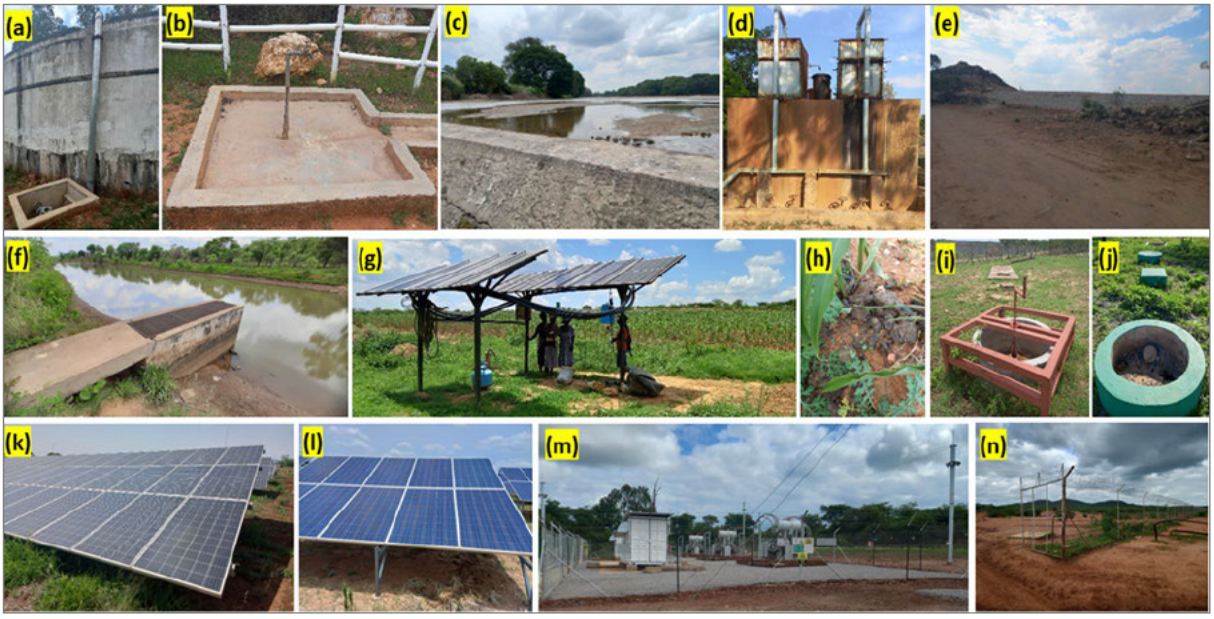


Figure 5.10: (a) Ongoing expansion of Esigodhini water treatment and supply system; (b) a private sector-funded community water supply scheme; (c) a sand dam at Tuli; (d) a sand dam water treatment and supply system at Ntepe; (e) ongoing construction of the Tuli-Moswa multi-purpose dam; (f) a dam supplying water at Mzinyathini irrigation scheme; (g, h) a solar-powered, drip-irrigated and organic manure fertilized community food and nutrition garden at Esibomvu; biogas digesters (i) supplying fuel for cooking and treated manure at a livestock farm and (j) energizing 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, (n) and in construction at Intratek site in Gwanda

However, any such efforts to improve WEF resources security need to be planned and implemented not from a sectoral but from a nexus perspective so as not to cause cross-purposes, conflicts and competition and trade-offs with other sectors and pillars. Ideally, interventions need to be synergistic and accrue improvements in all sectors and pillars, but this is not easy in real life due to the existence of interconnections between resources and sectors (Beekma *et al.*, 2021). Where and when win-win situations are initially unachievable, trade-offs must be understood and acknowledged so that the associated risks can be managed accordingly as further efforts to create synergies. Sometimes accounting for causes of trade-offs (e.g., from mismanagement or excluding some key stakeholders) is more likely to create a synergy than planning for a win-win situation from the outset (Howe *et al.*, 2014). There is need to critically interrogate the ongoing and proposed intervention efforts from an integrated nexus perspective and evaluate their cross-sectoral and overall impact to better inform decision-making and practice. Some of the potential, opportunities, synergies and risks associated with planned and ongoing WEF-related interventions are in Table 5.3.

Table 5.3: Summary of ongoing, operational and planned WEF-related practices, initiatives and their potential WEF-related synergies and risks across scales in Mzingwane Catchment and Umzingwane District in Zimbabwe

Water			Energy			Food		
Practice / intervention	**Nexus opportunities**	**Nexus risks / trade-offs**	**Practice / intervention**	**Nexus opportunities**	**Nexus risks / trade-offs**	**Practice / intervention**	**Nexus opportunities**	**Nexus risks / trade-offs**
Groundwater use	Deep aquifers; sand rivers	Groundwater depletion	Electrification	High solar potential; Grid capacity; Clean cooking; Net metering; Licencing cap	Insufficient generation and supply	Irrigation expansion (e.g., Beitbridge Juicing Citrus Estate); Irrigation rehabilitation	7900 ha; 4103 ha	Water and energy scarcity
Wastewater treatment and reuse (agriculture, domestic [e.g., retrofitting buildings], mining, industry, managed aquifer recharge)	Urban areas (Gwanda, Plumtree, Beitbridge)	Environmental health; Insufficient and dilapidated wastewater treatment plants; Energy scarcity	Renewable energy (solar PV, solar-powered water pumps and irrigation, solar water heaters)	High solar potential; Grid capacity; Additional energy and water resources; Mandatory solar water heaters	Competition for land; Groundwater depletion	Irrigation modernization	At least 3095 ha; Water savings	Increased energy consumption
Rainwater harvesting and storage, construction of small dams	Cyclones		Waste-to-energy (biogas digesters, landfills, cogeneration)	Urban waste, wastewater; Agricultural waste	Insufficient and dilapidated wastewater treatment plants; Energy scarcity	Waste-to-food (sludge beneficiation manure)	Urban waste, wastewater; Agricultural waste	Insufficient and dilapidated wastewater treatment plants; Energy scarcity
Removal of invasive alien vegetation	Water saving; Biomass for energy		Improving energy efficiency (generation and use)	Energy saving		Community food and nutrition gardens	Food security and nutrition	Water and energy scarcity
Improving water use efficiency in non-agricultural sectors	Water saving	Increased energy consumption	Modern clean cooking (e.g., stoves, LPG, biogas)	Improved air quality and human health;		Soil and water conservation (e.g., climate smart agriculture,	Increased productivity, enhance resilience,	Labour intensive, e.g., manual

				Conservation of forests		conservation agriculture	climate mitigation, soil and water conservation	conservation agriculture
Expanding and rehabilitating water (including bulk) and wastewater infrastructure	Clean water supply; Treated wastewater reuse	Water and energy scarcity				Agroecology (agro-forestry, tolerant and resistant varieties, small grains, underutilised crops, livestock production)	Food security and nutrition	Water for livestock
Water reallocation and inter-catchment transfers (Zhovhe Dam – Beitbridge – Musina)		Decreased water supply; Increased energy demand				Soil fertility management	Improved soil health	
Decommissioning of dams		Reduced water supply						

Sources: Key expert stakeholders; (CSIR, 2003; FAO, 2004; Murwira and Yachan, 2007; LBPTC, 2010b; LIMCOM et al., 2017; GoZ, 2018; Dickens et al., 2020; GoZ, 2020a; GoZ, 2020b; ZERA, 2021; GoZ, 2022c; GoZ, 2022a; GoZ, 2022b; GoZ, 2022d; GoZ, 2022f; GoZ, 2022g; GoZ, 2022h; GoZ, 2022i; GoZ, 2022j; GoZ, 2022e; GoZ, 2022k; GoZ, 2022l; ZERA, 2022; ZimVAC and FNC, 2022d; GoZ, 2023; ZERA, 2023; COMESARIA, n.d.; SNV, n.d.).

Where possible, intervention efforts can be bundled, into integrated synergistic packages. WEF-related plans on agenda such as increasing the developed irrigation area (e.g., to 4000 ha by 2025 in Matabeleland South) through rehabilitation, modernisation, expansion in Mzingwane Catchment and Umzingwane District need to consider the limits of available water and energy resources which are closely linked (Tarjuelo *et al.*, 2015; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2022c; ZimVAC and FNC, 2022e). This can then necessitate exploration of feasible alternative sources of water and energy resources. However, the Accelerated Irrigation Rehabilitation and Development Plan (AIRDP) is silent and not explicit on these key water and energy linkages (GoZ, 2020a; GoZ, 2023). Ongoing and planned dam construction projects (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 (Richter *et al.*, 2010; Branche, 2017; Lee and Kang, 2020). As such, multipurpose systems can provide WEF resource security even under climate extremes such as the current severe El Niño driven drought in southern Africa, thereby contributing to climate change adaptation (Berga, 2016). Similarly, small dams and reservoirs provide water resources, support agricultural activities, improve household food security, enhance entrepreneurial activities, diversify livelihood options, adapt to climate change (e.g., droughts) and contribute to sustainable and resilient development in rural communities (Senzanje *et al.*, 2008; Acheampong *et al.*, 2014; Saruchera and Lautze, 2019). From a nexus perspective and as adaptation strategies, (Mujere and Chanza, 2022) highlighted the WEF potential of multipurpose infrastructure, specifically the recently finished Tugwi-Mukosi dam (Masvingo Province), particularly on irrigated agriculture, hydropower generation, biofuel production and water supply. Although irrigation modernisation tends to save water at field scale, plans to change technology from 'low-efficient' surface methods to 'high-efficient' drip and sprinkler methods in Mzingwane Catchment (UNDP, 2022a; UNDP, 2022b; UNDP, 2022c) need to acknowledge and plan for associated trade-offs especially increased energy and water consumption (Rodríguez-Díaz *et al.*, 2011; Cremades *et al.*, 2016; Fernández García *et al.*, 2018; Taguta *et al.*, 2022).

5.3.1.3.1 Food / Agriculture

Approximately 47% of rural households in Zimbabwe apply the climate-proofed conservation agriculture 'Pfumvudza/Intwasa' practice, which is premised on soil and water conservation through reduced/minimum soil tillage/disturbance, ground cover, and crop rotations in rainfed crop production (Sharma *et al.*, 2022; ZimVAC and FNC, 2022d; ZimVAC and FNC, 2023a). The complete adherence to practices of conservation agriculture, such as the 'Pfumvudza/Intwasa' programme in Zimbabwe, has been reported to increase agricultural productivity and improve food security in arid and dry regions (Hove and Gweme, 2018; Mavesere and Dzawanda, 2023). However, Pfumvudza/Intwasa and similar climate-smart agriculture practices are persistently constrained by high labour requirements and human energy intensity, especially for female farmers, to the extent that some farmers code name the practices as Dhiga Ufe (Dig and Die) (Andersson *et al.*, 2011; Mango *et al.*, 2017; Tanyanyiwa *et al.*, 2022; Mutombo and Musarandega, 2023). Thus, successful upscaling of this nexus practice requires mechanisation which in turn requires energy in form of fuel. Development aid in both case studies should equally consider the energy sector and not focus only on improving food security (food handouts, livestock, sustainable agricultural technologies, best farming practices, value addition, irrigation, small grains, conservation agriculture, community nutrition gardens, horticulture, contracting farming) and water security (borehole rehabilitation) (GoZ, 2022l).

5.3.1.3.2 Water

Given that irrigated agriculture is currently under siege from inadequate electricity and water supply, irrigation plans including rehabilitation, expansion and modernization (technology conversion) (UNDP, 2022a; UNDP, 2022b; UNDP, 2022c) need to consider alternative energy and water sources. Alternative water sources include dams under or planned for construction, deep groundwater aquifers (approximately 0.9 litres per second) and alluvial aquifers, the latter which have a potential ranging from 24 $m^3/d/km$ to 133 $m^3/d/km$ along the major rivers (Alemaw *et al.*, 2008). The major alluvial aquifers are in Shashe River (180 km long, 63.83 km^2), Thuli River (120 km long, 19.77 km^2), Mzingwane River (160 km, 31.85 km^2, 0.975-12.35 Mm^3 of water, 200 m/d hydraulic conductivity, 20% specific yield, and 35% porosity), Bubi area (16 km, 1.82 km^2), Mwenezi River (93 km, 3.85km^2, 43% porosity, 14.4% specific

yield, 26.8 m/d hydraulic conductivity), and Mushawe River (1.60-2.45 m thick) (Kapangaziwiri *et al.*, 2021). However, these groundwater resources are finite, generally flow slowly, and their natural replenishment is gradual, sometimes lower than abstraction, thus requiring proper management including monitoring to minimize risks of resource depletion and land subsidence (Jiménez-Cisneros, 2014; Jatoth and Pawan, 2020; Jasechko *et al.*, 2024).

5.3.1.3.3 Energy

Alternative energy sources especially for irrigation and electrification include solar photovoltaics (PV) which have a high average daily practical photovoltaic potential (PVOUT) of 4.74 kWh/kWp with a global horizontal irradiation of 5.28 - 6.05 kWh/m^2 in Mzingwane Catchment (ESMAP, 2020; Solargis, n.d.; Solargis and ESMAP, n.d.). Although solar PV has limited long-term qualitative impact on land, increased deployment may potentially compete with other land uses (4 to 6 acres per MW) such as agriculture (UNEP, 2017; IRENA and FAO, 2021). The use of solar PV energy to pump water from sand rivers for domestic and irrigation is a transformative package for integrated WEF systems which fully leverage the nexus of energy, food and water by harnessing synergies among the sectors (IRENA and FAO, 2021). Off-grid solar pump irrigation, especially via groundwater and sand rivers, can decouple water and food systems from the risks of droughts (climate change), fuel costs, electricity power cuts and load shedding, thereby transforming WEF systems towards improved livelihoods, climate adaptation, climate mitigation, and resilience (IRENA, 2016). Wherein land is limiting or competed for, co-locating energy production with food production (agrivoltaics) and water bodies (floatovoltaics) can be useful to synchronise transformation of WEF systems, minimise resource competition, leverage synergies in water and land use, increase land-use efficiency and reduce water losses by open evaporation from surface water bodies in the hot and arid Mzingwane (Armstrong *et al.*, 2020; Gadzanku *et al.*, 2021; Khalifeh Soltani *et al.*, 2022). To leverage biodegradable waste, a circular economy can be promoted through upscaling biogas production for use in homes and institutions (schools, hospitals, clinics), while the byproducts can be used as manure in the production of food and fibre. As such, 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 (Creutzig *et al.*, 2015; Farghali *et al.*, 2022; Kabeyi and Olanrewaju, 2022). Das and Chirisa (2021) found that significant

amounts of nutrients can be recovered from wastewater from Harare City region and treated at Lake Chivero, the former which can be used for production of food with added benefits of pollution reduction and environmental and socio-economic wellbeing of the city region.

5.3.1.3.4 Using the WEF nexus approach to leave no-one behind

WEF nexus interventions for improving resource security need to be scaled and tailored for different contexts and settings, such as urban and rural. Mzingwane Catchment and Umzingwane District are mainly rural and underserved, and the abovementioned renewable energy and groundwater-based interventions comprise decentralised WEF solutions appropriate for remote rural and peri-urban areas without grid connection, but they can also supplement and complement the underperforming WEF service delivery in urban areas. Thus, in Mzingwane Catchment and Umzingwane District where agriculture is the mainstay of economy and livelihoods, the WEF nexus approach can holistically consider water, energy, food, land and climate in an integrated way that will address competing uses and identify ways to co-locate WEF systems on land to increase productivity (IRENA and FAO, 2021).

5.4 Conclusions and Recommendations

The objective of this study was to assess the state of the WEF nexus using mixed methods at catchment and district scale in southern Africa using Mzingwane Catchment and Umzingwane District in Zimbabwe as case studies. The qualitative research methods constituted interviews and discussion guides administered to key expert stakeholders in the WEF-related sectors in the case study areas. The quantitative research methods included conjunctive use of the iWEF model and established databases, reports and literature for reviewing secondary data and collecting information related to water, energy and food resources supply, demand, utilization and management.

The state of WEF nexus, and security and management of WEF resources in MC and UD is moderately sustainable and unbalanced, as evidenced by frequent water rationing, incidence of waterborne diseases (e.g., cholera), long episodes of electricity load shedding, widespread hunger and malnutrition, gold mining-land-water-environment trade-offs, and the slow (and some deteriorating) progress in achieving SDGs. Planned or ongoing efforts to improve WEF resource security in Mzingwane Catchment and Umzingwane District have potential

opportunities and risks that need to be understood and managed from a nexus perspective. The provision of clean energy for domestic use (cooking, lighting, heating), for example through electrification and biogas can promote a green circular economy for people, planet and prosperity in Mzingwane Catchment and Umzingwane District. Similarly, renewable energy, groundwater use and WEF systems co-location are scalable interventions that can achieve the multiple socioeconomic, environmental and livelihoods objectives in Mzingwane Catchment and Umzingwane District and other areas with similar context in southern Africa and beyond. Thus, the iWEF model is useful for bringing together WEF stakeholders to establish baseline state of the WEF nexus and status of implementation of the approach at multiple scales, which is an opportune platform for co-planning and harmonising activities among the WEF sectors.

Going forward, synergies and trade-offs of current practices and planned and ongoing WEF-related interventions need to be quantified for their economy-wide implications to inform upscaling. Promising integrated WEF solutions need piloting to demonstrate and measure the multisector impacts in the real world and inform the accelerated implementation of the WEF nexus approach for sustainable development. The six indicators in the iWEF model fail to give a comprehensive picture of quality of WEF resource security, and it needs to be expanded to include other pertinent indicators such as those for reliability of supply especially in the face of dire electricity load shedding, water rationing and water quality in Zimbabwe.

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6 A PEOPLE-CENTRED AND DATA-INFORMED METHODOLOGICAL FRAMEWORK AND GUIDELINES FOR CO-DEVELOPING INTEGRATED WATER–ENERGY–FOOD (WEF) NEXUS SCENARIOS

Abstract

Despite the research efforts around the water-energy-food (WEF) nexus, researchers concur that a gap exists in translating this theory into practice. This study used evidence from literature to develop generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. Some WEF nexus studies have used scenario planning for mapping and understanding the evolution of WEF systems and how nexus interventions can reach feasible and practical decision points. The key elements of WEF nexus scenario planning include; drivers of change, scenarios, pathways, scale, and analytic tools. Gaps in literature on WEF nexus scenario planning are related to (i) replicable methodological frameworks and guidelines, (ii) stakeholder engagement, (iii) application at a local scale, (iv) using the latest updated sixth phase of Coupled Model Intercomparison Project Shared Socioeconomic Pathways (CMIP6 SSPX-Y) pathways in WEF scenario planning for relevance, and (v) using the agricultural production-centric focus of Representative Agricultural Pathways (RAPs). Validation through interaction and with feedback from experts and stakeholders suggest that the developed generic people-centred and data-informed methodological framework and guidelines are reliable, rigorous and robust. To conclude, transdisciplinary approaches that include all stakeholders in problem identification, co-development, co-implementation and co-evaluation of WEF nexus scenarios are needed to ensure uptake and translation of the WEF nexus approach from theory to policy and practice. To achieve this, the study recommends using the proposed adaptable integrative framework and iterative guidelines and considering RAPs and the updated CMIP6 SSPX-Y pathways in planning people-centred WEF systems. Further studies need to review similar literature and synthesise the potential multidimensional implications of different pathways on future WEF nexus scenarios in different regions. Findings from this and other further research can be the evidence required to set the agenda and support implementation of the WEF nexus approach.

Keywords: pathway, resource security, sustainable development, WEF nexus

6.1 Introduction

Between 2 - 2.2 billion (approximately 26% of global population), 759 – 775 million (approximately 10% of global population), and 702 - 828 million (approximately 10% of global population) people, respectively, lack access to safe water, adequate and reliable electricity, and adequate food (FAO *et al.*, 2022; IEA, 2022; UN, 2023). Accordingly, the 'business-as-usual' resource demands in 2030 and 2050, relative to 2012, will increase by 40 – 100% for energy and 35 – 70% for food, which will require 20 – 55% more water and 10 – 30% more agricultural land (IRENA, 2015; FAO, 2022b; UN, 2022). As Albert Einstein said, "Insanity is doing the same thing over and over and expecting different results" (Wilczek, 2015), withstanding these current and future pressures on strategic resources requires a paradigm shift from conventional sectoral and fragmented resource management practices to integrated cross-sectoral approaches that seek to ensure balanced and integrated people-nature-economy sustainable management of water, energy, and food (UN-Water, 2018; Gallagher *et al.*, 2020). Such approaches to integrated resources management include the water-energy-food (WEF) nexus, scenario planning, and people-centred approaches.

The latest entrant among integrated resource management approaches is the polycentric water-energy-food (WEF) nexus approach, which highlights the interdependence of water, energy and food security and the supporting ecosystem of natural resources – water, soil and land (Hoff, 2011; WEF, 2011). The WEF nexus approach seeks to maximise synergies and minimise trade-offs in productive WEF systems for the collective security of WEF resources while maintaining the integrity and sustainability of ecosystem services (Hoff, 2011; Nhamo *et al.*, 2020). Nexus thinking and planning operates 'out of the sectoral boxes' at multiple spatial and temporal scales to promote co-ownership and engagement across all relevant sectors (Smith and Clausen, 2015; Grigg, 2019; Sadeghi and Sharifi Moghadam, 2021). The WEF systems and their nexus span and transcend multiple sectors and disciplines and thus require long-sighted approaches that minimize maladaptive pathways (Cremades *et al.*, 2019; Payet-Burin *et al.*, 2019; Nhamo *et al.*, 2020). Thus, the WEF nexus are complex and multidimensional social-ecological systems (SES) that affect and are affected by multiple actors, both expert and non-expert, including local communities and other stakeholders, all with divergent, and often entrenched, interests (Johnson and Karlberg, 2017; Hoolohan *et al.*, 2019; Terrapon-Pfaff *et al.*, 2021).

Visioning the future is integral to understanding interconnections between ecosystems and natural resources and responding to global and local environmental and sustainability challenges (van Vuuren *et al.*, 2012; Cremades *et al.*, 2019). Scenario planning has emerged as an effective technique for visioning the future and its strengths above traditional planning techniques (forecasting, prediction) include addressing complex, nonlinear, uncertain and nonstationary evolution of future conditions (Keskinen *et al.*, 2015; Hoolohan *et al.*, 2018; Uden *et al.*, 2018). Chermack (2018) and Cordova-Pozo and Rouwette (2023) extensively reviewed many scenarios and scenario planning definitions, which may focus on the process/aim/result, sometimes with highlights of participation or specific process considerations. This thesis and chapter adopt a simple definition of scenarios as combinations of quantitative pathways and qualitative storylines of the possible future state of the world characterised by emissions, climate projections and policy assumptions that define likely integrated human-climate-nature system development (O'Neill *et al.*, 2014; Hoolohan *et al.*, 2019). The scenario planning approach (art, tool, technique, method) explores a wide range of conditions and options, and assesses possible futures while challenging the status quo (Amer *et al.*, 2013; Hoolohan *et al.*, 2019; Cordova-Pozo and Rouwette, 2023). Relatedly, pathways are plausible trajectories of future conditions that describe a single component such as climate change, socioeconomic conditions, policy choices and technological changes (O'Neill *et al.*, 2014). For this study, we will focus on scenario planning which tend to exploratively and comparatively analyse outcomes between 'change' conditions and reference (no-change) conditions based on combined pathways as scenarios (O'Neill *et al.*, 2014; Borgomeo *et al.*, 2018). Scenario planning reveals new potential trends, key factors/drivers of change and actors, and the associated opportunities and threats (Star *et al.*, 2016; Dean, 2019). Common examples of pathways and scenarios for exploring interactions between complex social and environmental systems over the medium-to-long term are centred on agriculture (Valdivia *et al.*, 2015), societal development (O'Neill *et al.*, 2014), climate change (van Vuuren *et al.*, 2011a), ecosystems (MEA, 2005), environment (UNEP, 2012), energy (IEA, 2023), and agriculture/food and extended to land and water (FAO, 2022b; FAO, 2022a). However, the majority of these scenario planning applications tend to focus on isolated resource domains and thus can provide time-saving, consistent and comparable foundations for integrated and multidimensional scenario planning such as in the WEF nexus (Johnson and Karlberg, 2017; Hoolohan *et al.*, 2019).

Despite the hype of the WEF nexus approach in dialogue and research, its translation into practice is lagging due to the unavailability of empirical evidence, practical tools and case studies (Naidoo *et al.*, 2021). Similar to some of its predecessors such as the Integrated Water Resources Management (IWRM), WEF nexus thinking has traditionally been quantitative, techno-, econo- and resource-centric and neglected the 'people' social dimensions (Basco-Carrera *et al.*, 2017; Huckleberry and Potts, 2019; Jalonen *et al.*, 2022). This has led to oversimplifications and poor representation of the dynamic interactions between society, technology, and nature, and masking and sometimes accentuating the stark issues about inequal access to resources (Hoolohan *et al.*, 2019; Jalonen *et al.*, 2022; Newman *et al.*, 2024). While synergies and trade-offs in the WEF nexus vary in space and evolve with time, the majority of WEF nexus studies have stayed in historical and present time horizons, with limited application of scenario analysis, thus leaving unexplored the future dynamics and evolution of WEF systems within a changing context (Hoolohan *et al.*, 2018; Hoolohan *et al.*, 2019; Molajou *et al.*, 2021). All these shortcomings in the historic and current WEF nexus debates can be attributed to methodological challenges in including people in visioning and planning WEF nexus futures (Hoolohan *et al.*, 2018). To the best of our knowledge, there is paucity of frameworks and guidelines that can enhance rigour and value in research and inquiry (Liamputtong, 2009; Liamputtong, 2019; McMeekin *et al.*, 2020) for planning people-centred WEF nexus scenarios, although several WEF nexus frameworks and guidelines have been developed, published and reviewed (Purwanto *et al.*, 2021b). For example, what tools should be used and what drivers and pathways should be considered in planning WEF nexus scenarios are unclear. Thus, this work sought to develop a generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios, building on how scenario planning was previously applied in WEF nexus studies. Specifically, the study sought to (i) review key elements of WEF nexus scenario planning, and (ii) use the review findings and established protocols to develop a generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. This work is envisaged to guide WEF nexus researchers, planners and practitioners in exploring 'what if…?' questions of the future in a process that enhances capacity and whose outcomes can inform long-term integrative planning for robust, resilient and sustainable transitions of WEF systems (Hoolohan *et al.*, 2019).

6.2 Materials and Methods

6.2.1 Study approach

Social, economic, and political layers including the underlying power structures and dynamics determine the management of and access to WEF resources by all, including the most marginalized stakeholders (Jalonen *et al.*, 2022; Jalonen *et al.*, 2023). People are inextricably linked to their environment through livelihoods and this realisation is driving the marked paradigmatic shift from traditional top-down linear niche-specific scientific approaches (predominantly technical) to co-production by academics and non-academics in addressing the complex nature of contemporary sustainability challenges (Norström *et al.*, 2020; Maas *et al.*, 2022). This can be achieved through effective involvement and active contribution of those affected by and affecting the WEF nexus in discussions and analysis of their environment and their future, e.g., in 'nexus dialogues' (Almulla *et al.*, 2020), while leveraging wider sources of knowledge (local bottom-up and expert top-bottom) (Voinov and Bousquet, 2010; Newman *et al.*, 2020; Newman *et al.*, 2024). Such stakeholder engagement is a foundational step for embedding gender equality and social inclusion considerations that are missing in WEF nexus debates, and addressing issues of recognition and representation of diverse individuals, and equitable redistribution of resources (Jalonen *et al.*, 2022; Jalonen *et al.*, 2023). Thus, there are calls for integrating and reconciling the conventional top-bottom and nascent bottom-up approaches to leverage their complementarity and effectively link and locate local grassroots efforts within larger, structured programs (Scolobig *et al.*, 2015; Eicken *et al.*, 2021; Ding *et al.*, 2023).

Research and inquiry in WEF nexus scenario planning need to be situated within methodological frameworks that provide lens or vision and strengthen basis, rationale, rigour and value (Liamputtong, 2009; Liamputtong, 2019). A methodological framework is a structured guide to completing the process(es)/procedure(s) in research and enhances consistency, robustness, quality, standardisation, and trustworthiness (McMeekin *et al.*, 2020). A literature review by McMeekin *et al.* (2020) found that approaches for developing methodological frameworks are based on, among others, existing methods and guidelines, refinement and validation, and literature review (i.e., data extraction, synthesis and amalgamation). McMeekin *et al.* (2020) went on to propose a methodology for developing methodological frameworks, which was adopted in this study, and whose steps include (i)

identifying evidence to inform the methodological framework and guidelines, (ii) developing the methodological framework and guidelines, (iii) evaluating and refining the frameworks and guidelines, and (iv) application (ongoing) of the frameworks and guidelines (Figure 6.1).

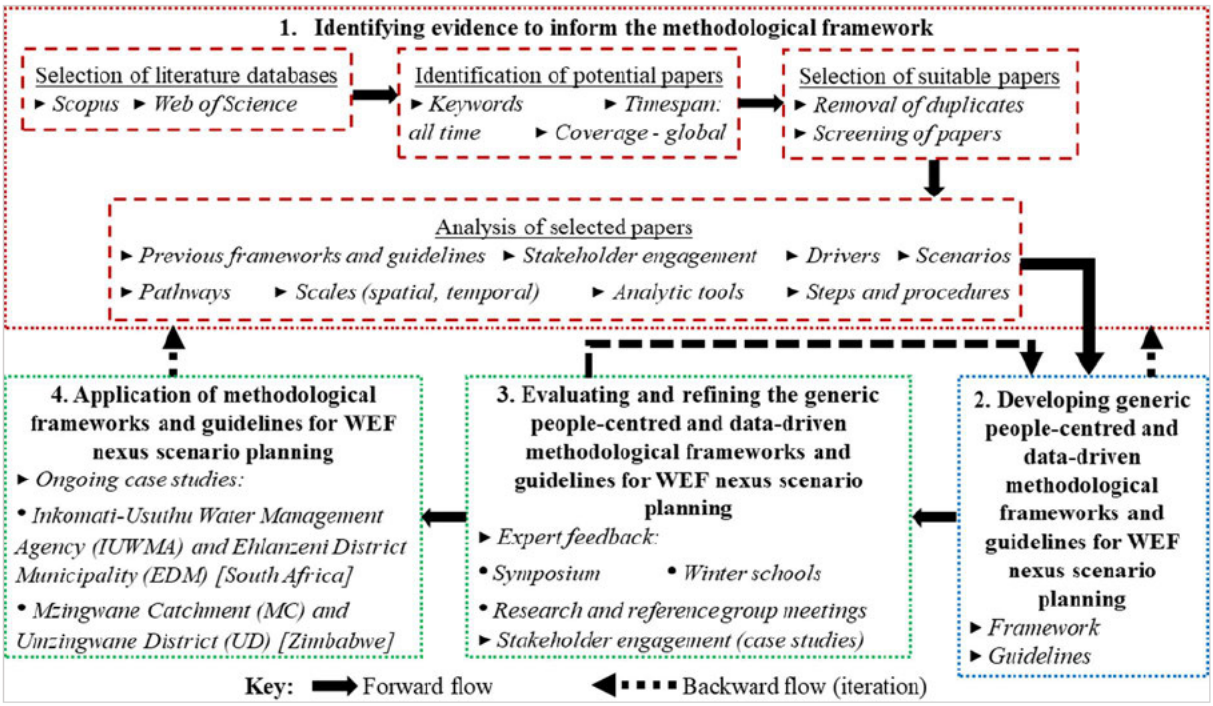


Figure 6.1: Study flowchart

Thus, this study used a mixture of approaches including literature review for new data, refinement and validation, as well as leveraging existing methods and guidelines in literature, to develop a generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. Compared to conventional frameworks, a people-centred framework prioritises people first and places their needs, perspectives, and active participation as the primary and central elements, actors and resource (Perera, 2010; Scolobig *et al.*, 2015; Verfuerth *et al.*, 2023). Such bottom-up frameworks enhance understanding the complexity of biophysical and social-ecological interactions between the landscape, resources, resource flows and different actors in socio-ecological systems (SESs) such as the WEF nexus (Johnson and Karlberg, 2017; Newman *et al.*, 2023).

6.2.2 Identifying evidence to inform the methodological framework

The review of literature was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page *et al.*, 2021a; Page *et al.*, 2021b). PRISMA was applied by Taguta *et al.* (2022) in systematically investigating the status and characteristics of existing WEF nexus tools which formed the basis for informing the development of an open access geospatial web-based integrative analytical tool for the water-energy-food nexus (iWEF) (Taguta *et al.*, 2023). The PRISMA steps in this study involved, among others, eligibility criteria, information sources, search strategy, literature screening, selection, data collection, defining data items, and analysis.

6.2.2.1 Eligibility criteria

The study used the population, indicator, comparison, outcome and study design (PICOS) strategy, which limits the number of irrelevant articles (Tacconelli, 2010; Methley *et al.*, 2014) (Table 6.1). The PICOS strategy informed the search strategy and the subsequent inclusion-exclusion criteria.

Table 6.1: The adapted PICOS strategy used for literature searching

PICOS	**Description**
Population	WEF nexus
Indicator	Scenario planning
Comparison	None
Outcome	Methodological frameworks and guidelines, and elements, and step/procedures of WEF nexus scenario planning
Study designs	Qualitative, quantitative and mixed

Given the relative novelty and fast-paced research in the WEF nexus field, broad eligibility criteria were adopted for publications mentioning the principle and practice of WEF nexus scenario planning. Consideration was given to peer-reviewed papers (articles, reviews), scientific book chapters, papers from proceedings, materials from special issue editorials, and institutional documents, including dissertations, theses, and technical papers, all written and published in English. It is acknowledged that there may be publications on the subject matter in other non-English languages, however these were excluded due to their requirements for

additional resources (human, time, financial) for professional translation into English language (Dobrescu *et al.*, 2021; Pieper and Puljak, 2021; Helbach *et al.*, 2022). In fact, majority of peer-reviewed scientific manuscripts are published in the English language (the academic lingua franca) and thus limiting studies accordingly is reported to have often insignificant impact on the findings and conclusions of systematic reviews (Nussbaumer-Streit *et al.*, 2020; Dobrescu *et al.*, 2021). However, the publication date, geographic scope, journal disciplines, and impact factors were kept open to capture all WEF nexus studies that potentially included scenario planning.

6.2.2.2 Information sources and search strategy

The potentially relevant studies in the literature were searched using the same search criteria within two online literature databases, Scopus and WoS CC (Web of Science Core Collection) (Last search on 10 January 2023). These two multidisciplinary databases were selected for their collection of high-quality scientific publications that allow systematic review, and their journal coverage that is remarkably greater than other common databases, even in natural science and engineering disciplines (Taguta *et al.*, 2022). The combination of these two main literature databases is highly comprehensive, selective, inclusive, reliable and of wider overall coverage, and they integrate content from numerous specialized databases with equal accessibility (Pranckutė, 2021). However, citation searches were also conducted for relevant publications in databases by government and non-government organizations with works on the WEF nexus, such as the Food and Agriculture Organization (FAO), United Nations Economic Commission for Europe (UNECE) and the International Renewable Energy Agency (IRENA) (Hoolohan *et al.*, 2019). The search criteria in the two databases (Scopus and WoS CC) involved searching topics using Boolean expressions (Table 6.2).

Table 6.2: Terms used in searching literature in Scopus and WoS CC databases

Search topic (first row)	Second row	Search topic (third row)
(water-energy-food) OR (water-food-energy) OR (energy-food-water) OR (energy-water-food) OR (food-energy-water) OR (food-water-energy) OR wef OR wfe OR efw OR ewf OR few OR few	AND nexus	AND (scenario* OR plan* OR future OR predict* OR forecast* OR pathway OR "representative concentration pathway" OR RCP OR "shared socio-economic pathway" OR SSP OR "Coupled Model Intercomparison Project Phase" OR CMIP OR "representative agricultural pathway" OR RAP)

Selecting these two databases was also a preemptive measure against predatory journals whose prevalence is generally low in Scopus and WoS CC (Somoza *et al.*, 2016). All records obtained from Scopus, WoS CC, and other databases were combined to facilitate the removal of duplicates and the screening process. The full list of compiled search records is available at Articles database_WEF nexus scenario planning - Google Sheets.

6.2.2.3 Screening and selection of studies

In line with the objectives of this systematic review, the titles, abstracts, and keywords of the searched studies were reviewed and manually screened in a spreadsheet for literature selection. The manual screening was in favour of publications (i) on the application of scenario development, planning and analysis in the WEF nexus approach in theory and practice, (ii) in a defined applied geographic scope (location, place, area) and scale (spatial, temporal), (iii) capturing at least all three components of the WEF nexus: water, energy, and food, with the possibility of additional related dimensions such as land, climate, environment, ecosystem and economy, and (iv) on the use of established pathways and protocols such as SSPs, RCPs, RAPs, policy and intervention pathways/response strategies. Sometimes, terms such as 'land', 'agriculture', 'irrigation' or 'irrigated agriculture' were considered proxies for food since they are directly linked to food production. Publications missing any of the water, energy and food dimensions and their proxies were excluded (Cullis *et al.*, 2018; Wang *et al.*, 2018; Tan *et al.*, 2020; Barhagh *et al.*, 2021). Eventually, the eligible papers were retrieved for review.

6.2.2.4 Data collection

A data extraction sheet was designed in simple, adaptable, and functional MS Excel based on the study objectives and key data on the selected papers were manually extracted from the eligible studies and organized in the data extraction sheet. The manual data extraction technique was adopted and used because humans are creative and have a holistic view of the process than fully automated or semi-automated tools such as those based on artificial intelligence (AI) and support vector machine (SVM) for information extraction (Schmidt *et al.*, 2021; Wagner *et al.*, 2022; de la Torre-López *et al.*, 2023). The key data were organized in the spreadsheet in columns for publication details (author, year, title), case study (location, country, continent), drivers, scenarios, pathways, scales (spatial, temporal), analytic tools, involvement of stakeholders, and steps/procedures. These were identified as key elements for WEF nexus scenario planning, and they are major components used in developing the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

6.2.2.5 Definitions of data items and analysis of studies

All evidence of scenario planning in the WEF nexus gathered from the literature was analysed systematically, and the results were presented narratively, quantitatively and visually. The key components defining scenarios and scenario planning include: (i) a future orientation (temporal scale or planning horizon), (ii) a concern for external contexts (drivers of change), (iii) having a narrative form (pathways), (iv) plausibility, (v) being part of a systemized set, (vi) of meaningfully different alternatives (pathways), (vii) aim to raise awareness (stakeholder engagement), and (viii) seek to increase performance in the future based on the strategies adopted in the present (interventions) (Cordova-Pozo and Rouwette, 2023). Thus, the analysis criteria for this study were mainly the elements of scenario planning, including methodological frameworks and guidelines, scenarios, pathways, scales, analytic tools, involvement of stakeholders, and steps/procedures. These elements of scenario planning are defined in Table 6.3, except for those defined earlier including scenarios, scenario planning and pathways (Section 6.1), and methodological framework (Section 6.2.1).

Table 6.3: Definitions of terms for the analysis criteria, i.e., elements of scenario planning

Term	**Definition**
Methodological guidelines	Systematically developed reproducible, reusable and empirically validated general statements, instructions, procedures, steps and recommendations, e.g., checklist, flow diagram, or structured text, that assist on how to execute a process or task in a replicable manner (Klein, 2002; InformedHealth.org, 2006; Schlussel *et al.*, 2023).
Stakeholder engagement	The involvement of individuals in a moral, strategic, positive, and/or pragmatic and dynamic context of interaction, mutual respect, dialogue, and change, to obtain buy-in and co-plan and co-implement allocation of resources (Kujala *et al.*, 2022; Lock *et al.*, 2023).
People-centred approaches	Bottom-up approaches (predominantly social/institutional) that prioritise people first and place them as the primary and central element, actors and resource (Perera, 2010; Scolobig *et al.*, 2015; Verfuerth *et al.*, 2023), to enhance understanding the complexity of biophysical and social-ecological interactions between the landscape, resources, resource flows and different actors in socio-ecological systems (SESs) such as the WEF nexus (Johnson and Karlberg, 2017; Newman *et al.*, 2023).
Data-informed approach	Unlike a data-driven approach that relies solely on and prioritises data (Pantović *et al.*, 2024), a data-informed approach integrates and balances both data and human reasoning to make contextualised decisions (Wulff and Finnestrand, 2023; Zaimoglu *et al.*, 2023; Abac, 2024; Haase *et al.*, 2024).
Drivers of change	Natural or human-induced important and uncertain driving forces/factors that directly or indirectly cause a change in a WEF system's state, behaviour or ecosystem/environment (Carter *et al.*, 2001; MEA, 2005; UNEP, 2012).

Spatial scale (for a model or case study)	A spatial extent or application level under consideration such as ecological, hydrological and administrative, sometimes measured by area, distance, volume or length (Dai *et al.*, 2018; Ladau and Eloe-Fadrosh, 2019; Mabhaudhi *et al.*, 2023).
Temporal scale (planning horizon)	The extent of the duration or the period under consideration (Quijas and Balvanera, 2013; Ladau and Eloe-Fadrosh, 2019).
A WEF system tool (or model or application)	An intellectual construct of relationships, including mathematical, that simplify and represent reality, and capture WEF spatial and/or temporal dynamics and feedback (Taguta *et al.*, 2022).

Examples of pathways in this study include those for climate change (e.g., RCPs), socioeconomic conditions (e.g., SSPs), agricultural development (RAPs), policy (and strategy) choices, interventions and technological changes. The interventions were referenced to the sector in which they are implemented, and their effect is planned to impact resource production, generation, supply, use, and consumption. These categories of interventions for the pathways include cross-cutting or overarching and those for specific sectors, including water, energy and food/agriculture. For distinguishing between top-down and people-centred approaches in the decision-making component of WEF nexus scenario planning in this study, use was made of the elaboration by Scolobig *et al.* (2015), particularly on explicit and active engagement and participation of relevant stakeholders including the public, such as communities. This is perceived as a prerequisite and entry point for people-centred WEF nexus scenarios planning.

Analytic modelling tools include the sectoral and integrated ones, some of the latter category which were documented by Taguta *et al.* (2022). The demarcation of spatial and temporal scales is provided in Table 6.4.

Table 6.4: Different spatial and temporal scales and resolutions considered in the study

Spatial scale (Dai *et al.*, 2018; Taguta *et al.*, 2022)			**Temporal (Bruaset and Sægrov, 2018)**		
Local	*Medium*	*Large*	*Short-term (operational)*	*Mid-term (tactical, intermediate)*	*Long-term (strategic)*
Household, field, farm, community, village, town, city, municipality, district	Metropolitan, in-country region, provincial, national, state, county, sub-catchment, watershed, in-country river basin/catchment)	Transboundary river basin/catchment and aquifer, economic region, continent, global	0 to 5 years	6 to 10 years	> 10 years

6.2.3 Developing the methodological framework and guidelines

As guided by McMeekin *et al.* (2020), the evidence gathered in Sections 6.2.1 - 6.2.2 was used for developing the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. While the frameworks and guidelines from literature were used as the foundation for developing the methodological framework and guidelines, the elements of WEF nexus scenario planning from literature were used as building blocks and for enriching the methodological framework and guidelines. The development process was iterated with feedback from experts and the project team, and sometimes going back to Sections 6.2.1 - 6.2.2 for refining the draft methodological framework and guidelines (McMeekin *et al.*, 2020).

6.2.4 Evaluating and refining the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios

In line with the methodology proposed by McMeekin *et al.* (2020), initial evaluation and revision of the proposed framework and guidelines for co-developing WEF nexus scenarios were through discussions and interactions with expert and non-expert stakeholders, while further validation is ongoing through application in two districts and two catchments in South Africa and Zimbabwe. Several multidisciplinary and transdisciplinary platforms were used to

present, get feedback and validate the structure, content and logic of the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. The first event was a special session at the 23rd WaterNet/WARFSA/GWP-SA Symposium on Integrated Water Resources Management for Sustainable Development in Eastern and Southern Africa in 2022 (Sun City, South Africa). The multidisciplinary audience had an almost equal composition of emerging and experienced scientists coming from a broad spectrum of sciences from all over the world.

The generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios were also presented to two cohorts (2023 and 2024) of the WEF Nexus Winter School (now Advanced School) in Pretoria (South Africa) whose multidisciplinary audience had more early career researchers than experienced scientists from all over the world. The two have also been subject of discussion and interrogation in the multidisciplinary Reference Group Meetings for the Water Research Commission projects "From Theory to Practice: Developing a Case Study and Guidelines for Water-Energy-Food (WEF) Nexus Implementation in Southern Africa - WRC2019/2020-00007" and "Operationalising the Water-Energy-Food Nexus for Delivering on Socio-Economic Development - WRC2022/2023-00910".

The generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios were presented and discussed in four transdisciplinary sub-catchment management forum meetings in Inkomati-Usuthu Water Management Area (IUWMA) and in the Ehlanzeni District Municipality (EDM) which partly overlaps with IUWMA in South Africa. In Zimbabwe, the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios were presented and discussed through interactions with transdisciplinary WEF-related experts and stakeholders in Mzingwane Catchment (MC) and Umzingwane District (UD). These stakeholder engagement activities formed the initiation processes for the ongoing co-development of WEF nexus scenarios in the four case studies in South Africa (IUWMA and EDM) and Zimbabwe (MC and UD), all which are at the modelling phase of the WEF nexus scenarios.

The fifth event was a special session at the 25rd WaterNet/WARFSA/GWP-SA Symposium on "Enhancing Sustainability: Upscaling Innovations and Best Practices for Integrated Catchment and Water Resources Management (ICWRM) in Eastern and Southern Africa – Leaving No

One Behind" in 2024 (Maseru, the Mountain Kingdom of Lesotho). The multidisciplinary audience had an almost equal composition of emerging and experienced scientists coming from a broad spectrum of sciences from all over the world.

6.3 Results and Discussion

The main findings of this study are discussed here, related to the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

6.3.1 Literature search

For gathering evidence for developing the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios, the database searches yielded 2010 and 794 records with and without duplicates, respectively (Figure 6.2). Screening the publications by the inclusion-exclusion criteria yielded 173 articles on WEF nexus scenario planning that were retrieved and analysed.

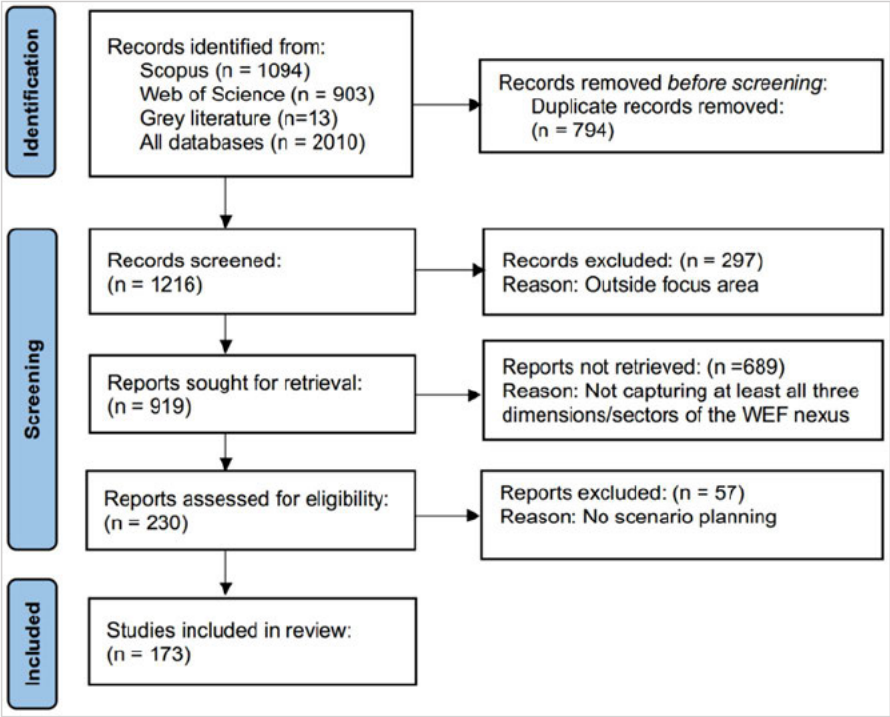


Figure 6.2: PRISMA 2020 flow chart and outcomes of article selection

Using evidence that was gathered in the retrieved literature, the following sub-sections seek to inform would-be WEF nexus scenario planners on elements to consider when planning WEF nexus scenarios, including frameworks, guidelines, potential pathways, scales, analytic tools and the engagement of stakeholders.

6.3.2 Methodological frameworks and guidelines for WEF nexus scenario planning

The WEF nexus scenarios in the reviewed studies were developed and analysed as either one or a combination of plausible pathways, at specific spatial and temporal scales, using either one or a combination of analytic tools. At the same time, some did or did not engage stakeholders and explicitly specify their methodological frameworks and guidelines. Despite the inevitable value of methodological frameworks and guidelines for enhancing the basis, rationale, rigour and value in WEF nexus scenario planning (Liamputtong, 2009; Liamputtong, 2019), around 15% of the reviewed studies did not explicitly provide and mention the frameworks that they used (Figure 6.3a). This potentially undermines the consistency, robustness, quality, and trustworthiness of WEF nexus scenario planning studies (McMeekin *et al.*, 2020).

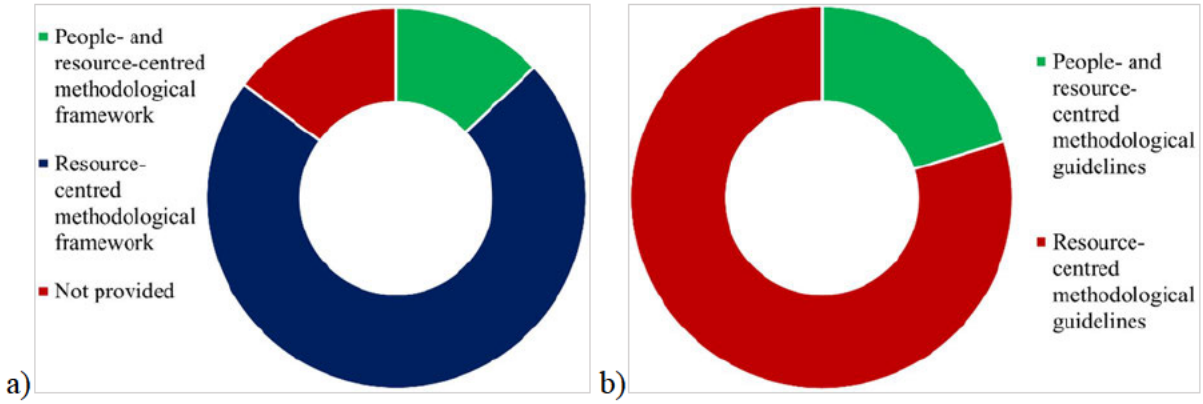


Figure 6.3: Types of methodological (a) frameworks and (b) guidelines in WEF nexus scenario planning studies

The methodological frameworks and guidelines provided in WEF nexus scenario planning studies differed in structure and content among studies, especially on the key elements, steps followed, objectives, methods and approaches, and procedures. However, a majority of the reported methodological frameworks (72%) and guidelines (80%) are resource-centred and not people-centred (Figure 6.3). A striking difference between the people-centred and resource-centred methodological frameworks and guidelines is the inclusion and exclusion, respectively, of people including stakeholders. The exclusion of people (e.g., stakeholders) is a formidable limitation, gap and need which denies the opportunity for validation of key elements, models and outcomes through sustained development and iteration with stakeholders, for co-exploration of WEF nexus scenarios (Kliskey *et al.*, 2023). Stakeholder engagement and participation is the foundation of participatory scenario development that puts people at the centre of planning and developing WEF nexus futures. The following sections will unpack the key elements in WEF nexus scenario planning which are used to propose and develop the generic people-centred and data-informed methodological framework and guidelines for systematically co-developing integrated WEF nexus scenarios. These key elements include drivers of change, stakeholder engagement, pathways, spatial and temporal scales, and analytic tools.

6.3.2.1 People in planning WEF nexus including RAPs

One of the intrinsically complex challenges of the WEF nexus approach is accounting for and balancing the diverging views and interests of multiple stakeholders from various sectors and at different scales (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017). Despite the importance

of stakeholder input in co-planning WEF nexus scenarios, a minority (28%) of reviewed studies explicitly reported that they engaged stakeholders from their study areas. In comparison, 72% did not mention engagement of stakeholders (Figure 6.4a).

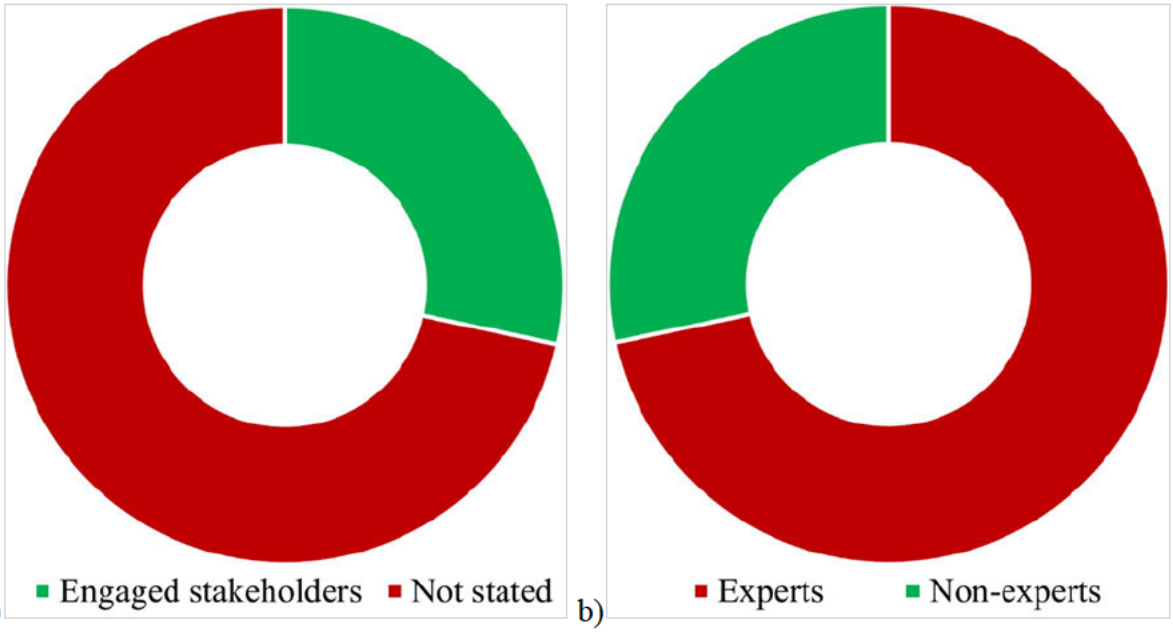


Figure 6.4: Stakeholder (a) engagement and (b) types in WEF nexus scenario planning studies

The lack of stakeholder participation and their individual preferences is a weakness in scenario planning (van Vuuren *et al.*, 2012; Casazza *et al.*, 2021). However, the majority (72%) of the reported stakeholders were experts and technical stakeholders (Figure 6.4b). According to Casazza *et al.* (2021), household and people's behavioural attitudes are generally excluded when assessing resource consumption scenarios. The selective inclusion and isolation of stakeholders, e.g., researchers and planners, while excluding those who live and work in the WEF systems, , e.g., farmers, fishermen and growers, in WEF nexus scenario planning denies, limits and compromises understanding and modelling the trajectories of change in broad level interactions in WEF systems (Kliskey *et al.*, 2023). Similarly, this may place a bias on the views of technical experts over those of non-experts (Johnson and Karlberg, 2017).

The stakeholders engaged in previous studies on planning WEF nexus scenarios emanated from multiple sectors and disciplines including public and private sectors, as well as water, energy, agriculture/food, climate, and environment. Thus, planning WEF nexus scenarios, including RAPs, is transdisciplinary and multidisciplinary. The role of stakeholders included weighting WEF nexus assessment criteria (Nasr and Zahran, 2016), identifying local WEF challenges,

considerations and preferences (Almulla *et al.*, 2020), selection of interventions (infrastructural plans, adaptation options) and their performance objectives/needs/metrics (Siderius *et al.*, 2021), identifying relevant policies and options or portfolios (solutions) (Knox *et al.*, 2018), validating scenarios (Johnson and Karlberg, 2017) and identifying gaps for future exploration (Khan *et al.*, 2020). A study by Casazza *et al.* (2021) showed that communication actions for information and education would be most appropriate to promote sustainable citizen behaviour and increase the level of resource savings and reduce GHG emissions, compared to resource pricing strategies (Casazza *et al.*, 2021). According to Casazza *et al.* (2021), monetary policies were not equally effective for reducing household resource consumption most probably due to water, energy (electricity, gas) and food being basic household resources. Thus, stakeholder engagement is an integral element in people-centred and data-informed methodological frameworks and guidelines for co-developing integrated WEF nexus scenarios. A paradigm shift is needed to thinking and viewing the involvement of people as a process of integrated knowledge generation and co-production, and stakeholder engagement was identified and taken forward towards the development of people-centred and data-informed methodological frameworks and guidelines for co-developing integrated WEF nexus scenarios (Kliskey *et al.*, 2023).

6.3.2.2 Drivers of change and pathways in planning WEF nexus scenarios

The security of WEF resources is under pressure from complex drivers of change in a degrading environment, including climate change, ecological, social, economic, and institutional dynamics (Mabhaudhi *et al.*, 2016; UN-Water, 2018). Exploring future WEF developments through scenario planning requires understanding how future evolution in these key drivers/forces/factors of change may impact the WEF systems' ability to satisfy the economic, social and environmental demands for resources (Bijl *et al.*, 2018). Some of the key drivers (or forces) of change that were considered in WEF nexus scenario planning are highly uncertain and important forces (Figure 6.5) (Johnson and Karlberg, 2017).

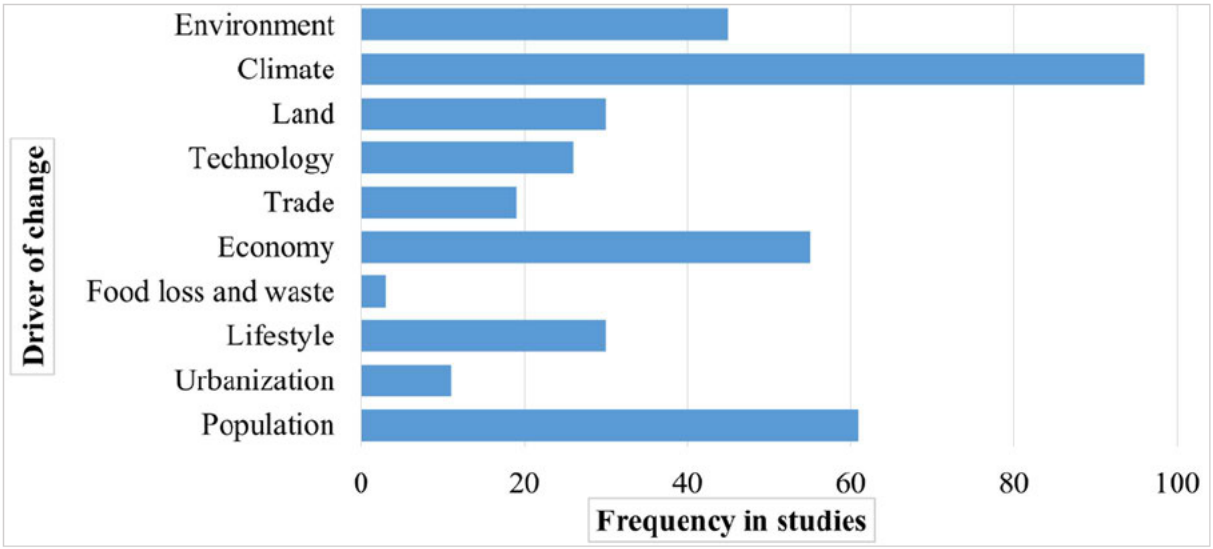


Figure 6.5: Drivers that force changes in WEF systems as considered in WEF nexus scenario planning studies

The socioeconomic category of drivers of change included population growth, urbanization, migration, lifestyle (diets, consumption patterns, and food waste and loss), economic development (growth, trade,), the evolution of agricultural and energy systems, and technology (Figure 6.5) (Hejazi *et al.*, 2014; Bijl *et al.*, 2018; van Vuuren *et al.*, 2019). Several studies at global (Hejazi *et al.*, 2014; Sušnik, 2018; Wild *et al.*, 2021) and local scales (Koundouri and Papadaki, 2020) have shown that socioeconomic factors drive the scale of economic activity and sectoral interactions among WEF dimensions, and will exacerbate pressure on water resources in the 21st century.

The climate category of drivers of change includes climate change, climate variability and climate action (Hoolohan *et al.*, 2019), while the environmental category of drivers of change include the use and degradation of ecosystems and resources, e.g., land, as well as obligations for downstream and ecological/environmental flows (Figure 6.5) (Bremer *et al.*, 2018; da Silva and de Moraes, 2018). Climate variability and change cause fluctuations in WEF resources security and trigger trade-offs in the WEF nexus (Mpandeli *et al.*, 2018). Some of these drivers of change are interconnected, for example socioeconomic assumptions dictate the future possibility space of climate change (Nasrollahi *et al.*, 2021). However, the future evolution of these drivers is highly uncertain and the same can be said about their likely impact on WEF nexus futures. Together with policies and interventions, the aforementioned drivers of change force the trends or conditions in pathways that integrate to form WEF nexus scenarios (Johnson

and Karlberg, 2017; Karabulut *et al.*, 2019; Kulat *et al.*, 2019). Thus, drivers of change inform pathways and scenarios and they were taken forward for developing people-centred and data-informed methodological frameworks and guidelines for co-developing integrated WEF nexus scenarios.

6.3.2.2.1 Pathways of socioeconomic and climate change

Projections of future societal and climate change contribute to characterising societal risks and response options and improving understanding of the climate system (O'Neill *et al.*, 2016). The pathways of societal and climate change used in WEF nexus scenario planning include ad hoc and established pathways. The latter category of pathways of societal and climate change include the Coupled Model Intercomparison Project (CMIP) SSPs and RCPs, respectively, and their predecessors. These CMIP pathways, scenarios, and model results, have become standard reference inputs for work concerning climate and societal change science, impacts, vulnerability, adaptation, and mitigation. A marked evolution of pathways of societal and climate change from a climate-centric to an increasingly societal development-centric concept occurred in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) wherein SSPs and RCPs were introduced in the global community (World Bank, n.d.). Changes in socioeconomic and climate change have also been integrated in WEF nexus scenarios through the Global Scenario Group (GSG) scenarios (Hussien *et al.*, 2017). The GSG scenarios vision six future worlds characterised by conventional worlds (market forces, policy reform), barbarization (fortress world, breakdown), and a great transition (eco-communalism, new paradigm) (Kemp-Benedict *et al.*, 2002).

6.3.2.2.1.1 Common CMIP5 and pre-CMIP5 socioeconomic and climate change pathways in WEF nexus scenario planning

The five SSPs describe plausible alternative trends in the evolution of society and natural systems over the 21st century, including future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources (Appendix J) (van Vuuren and Carter, 2014; O'Neill *et al.*, 2017; Riahi *et al.*, 2017).

A minority (about 11%) of the reviewed studies used SSPs to represent socio-economic change dynamics in WEF nexus scenario planning. SSP2 is the most popular (37%) baseline or business-as-usual (BAU) pathway in WEF nexus scenario planning studies because it (i) uses the current trends to present the 'normal development or growth' of a socioeconomic system without the intervention of a targeted policy or activity, (ii) provides a control from which alternate scenarios relating to a specific policy (or technology) are developed and evaluated for impacts, and (iii) represents a future with intermediate challenges to mitigation and adaptation (Figure 6.6a) (Fricko *et al.*, 2017; Godínez-Zamora *et al.*, 2020; Nong and Simshauser, 2020).

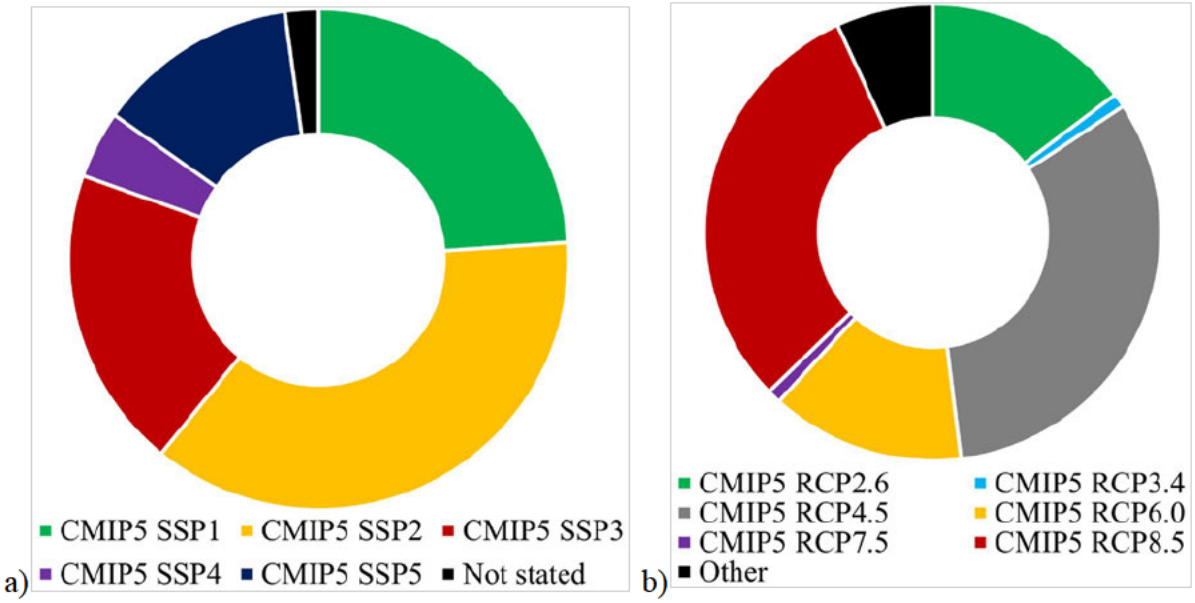


Figure 6.6: Application of (a) pre-CMIP5 and (b) CMIP5 socioeconomic and climate change pathways in WEF nexus scenario planning

The hierarchy of popularity of SSPs in WEF nexus scenario planning studies is followed by SSP1 (24%, taking the green road of sustainability (van Vuuren *et al.*, 2017)) and SSP3 (20%, regional rivalry (Fujimori *et al.*, 2017)), both depicting two different worlds of challenges to mitigation, adaptation and sustainability in WEF nexus futures. The next frequent pathway is SSP5 (13%, conventional fossil-fuelled development (Kriegler *et al.*, 2017)), followed by the least frequent SSP4 (4%, a road divided by inequality) (Calvin *et al.*, 2017) (Figure 6.6b). WEF systems respond to and evolve with changes in socio-economic conditions. WEF nexus scenario planning studies at multiple scales have shown that all other SSPs, except SSP1, will likely exacerbate future food production, energy generation and consumption, water

consumption and scarcity, agricultural area, GHG emissions, and overall nexus state, leading to further resources degradation and environmental pressure (Borgomeo *et al.*, 2018; Momblanch *et al.*, 2019; van Vuuren *et al.*, 2019; Koundouri and Papadaki, 2020). For the Duhok city in Iraq, Hussien *et al.* (2017) found that the 'fortress world' scenario by the GSG would accrue the highest increase in the household demand for WEF resources in the future, due to the increase in high income households which leads to increase in the family size, followed by, in descending order, the 'market forces', 'policy reform', and the 'great transition' scenarios.

The RCPs describe trajectories for the development of emissions and concentrations of different atmospheric constituents affecting the radiative forcing of the climate system over time (Appendix K) (van Vuuren and Carter, 2014). About 30% of reviewed literature applied established climate change pathways (RCPs and Special Report on Emission Scenarios (SRES)) in their studies. The descending order of frequency in applying climate change pathways was RCP4.5 (32%, medium-low emission (Thomson *et al.*, 2011)) and RCP8.5 (30%, high emission (Riahi *et al.*, 2011)), followed by RCP2.6 (15%, low emission (van Vuuren *et al.*, 2011b)) and RCP6.0 (14%, medium-high emission (Masui *et al.*, 2011)), others (7%), with RCP7.5 (1%) and RCP3.4 (1%) coming last (Figure 6.6b) (Moss *et al.*, 2010; van Vuuren *et al.*, 2011a; World Bank, n.d.). These emission and climate pathways are characterised by stringent mitigation to keep global warming likely below 2°C above pre-industrial temperatures (RCP2.6), collective climate action to keep global average temperature rise of no more than 2 ºC and 3 ºC above pre-industrial temperature levels by the year 2100 (RCP4.5), stabilization of total radiative forcing shortly after 2100 without overshoot (RCP6.0), and a 'business as usual' absence of stringent climate mitigation that leads to an estimated global average temperature increase of approximately 5-6ºC by 2100, relative to pre-industrial temperature levels (RCP8.5) (Hausfather and Peters, 2020; World Bank, n.d.). However, RCP2.6 is generally no longer attainable given the insufficient global emission mitigation efforts (Sanderson *et al.*, 2016; UNEP, 2023), recent breaches of historic annual warming records (2023, 1.45 ± 0.12°C) and the record high annual warming that is expected in the near future (2024-2028, > 1.5°C) relative to the pre-industrial baseline (1850-1900) (WMO, 2024).

Robust WEF systems, especially infrastructure with a long-life expectancy including dams, irrigation schemes and hydropower systems, hinge on uncertain hydro-climatic drivers and need to account the potential impacts of a changing climate (Enayati *et al.*, 2021). At various scales, studies on WEF nexus scenario planning found that low emission and stringent

mitigation climate pathways will likely lead to favourable future WEF nexus states including improved ecological/environmental footprints, lake water levels, water and energy budgets and quality, food production, and GHG emissions, in the 21st century (Hejazi *et al.*, 2014; Bakhshianlamouki *et al.*, 2020; Lee *et al.*, 2020; Schull *et al.*, 2020; Nasrollahi *et al.*, 2021).

The pre-CMIP5 SRES pathways are four families of socioeconomic futures that span the dimensions of globalized vs. regionalized development and economic vs. environmental orientation (O'Neill *et al.*, 2014). The SRES family of pathways that were applied in WEF nexus scenario studies include A1b, B1, A2, and B2 (Appendix L) (IPCC, 2000; Keskinen *et al.*, 2015; Khan *et al.*, 2017; da Silva and de Moraes, 2018). Other studies incorporated ad hoc climate change pathways outside the established IPCC and CMIP ones, for example climate signals and stress tests involving levels of temperature and precipitation changes (Yang *et al.*, 2016) such as dry, semi-dry, intermediate semi-wet, wet, warmer, cooler, severe, cloudy, humid, sunny and arid climate (Karlberg *et al.*, 2015; Karan *et al.*, 2018; Ding *et al.*, 2021; Qin, 2021). For major Arizona crops (USA), Berardy and Chester (2017) predicts that temperature increases of 1°C above the baseline could decrease yields by up to 12.2% and increase irrigation water and energy (mainly electricity) by about 2.6% with associated increases in GHG emissions. In the Mekong River basin, Meng *et al.* (2021) predicted declines in hydropower generation and irrigation water supply under 1.5 °C and 2 °C warming scenarios, with the latter scenario greatly undermining the co-benefits between the hydropower generation and irrigation than in the former scenario.

6.3.2.2.1.2 Integrating CMIP5 socioeconomic and climate pathways in WEF nexus scenario planning studies

The drivers of change that affect WEF systems are interconnected. For example, climate pathways (e.g., RCPs) provide the background for implementing socioeconomic assumptions (e.g., SSPs) consistent with emission and climate change outcomes (Hausfather and Peters, 2020; Nasrollahi *et al.*, 2021). On the other hand, socioeconomic and technological change assumptions (e.g., SSPs) characterise worlds in which societal trends make mitigation of, or adaptation to climate change harder or easier, without explicitly considering climate change itself (van Vuuren and Carter, 2014; Borgomeo *et al.*, 2018). Some studies reported that the impacts of the human dimension, i.e., socio-economic factors, on the nexus will be greater than

those caused by climate change (Hoang *et al.*, 2019; Momblanch *et al.*, 2019; Gallagher *et al.*, 2020; Guan *et al.*, 2020; Khan *et al.*, 2020). On the other hand, other studies show that climate change impacts will be more significant than socioeconomic changes on WEF nexus futures (Jin *et al.*, 2018). This shows that the interactions and interconnections between WEF systems and drivers of change depend on the context and vary in space and time. Thus, WEF nexus scenario planning studies should employ integrated impact frameworks to assess interactions between the multiple driving factors and pathways and capture the consequences of and uncertainty in global change. Such an approach increases possibilities for robust adaptation policy making and relevant strategic and action planning of WEF systems now and in the future (Hoang *et al.*, 2019; Momblanch *et al.*, 2019).

Although they were later officially integrated in the sixth phase of the Coupled Model Intercomparison Project (CMIP6), the CMIP5 societal development-centric SSPs and climate-centric RCPs were used together in some WEF nexus scenario planning studies to assess the combined impacts of changes in socioeconomic and climate conditions (Figure 6.7).

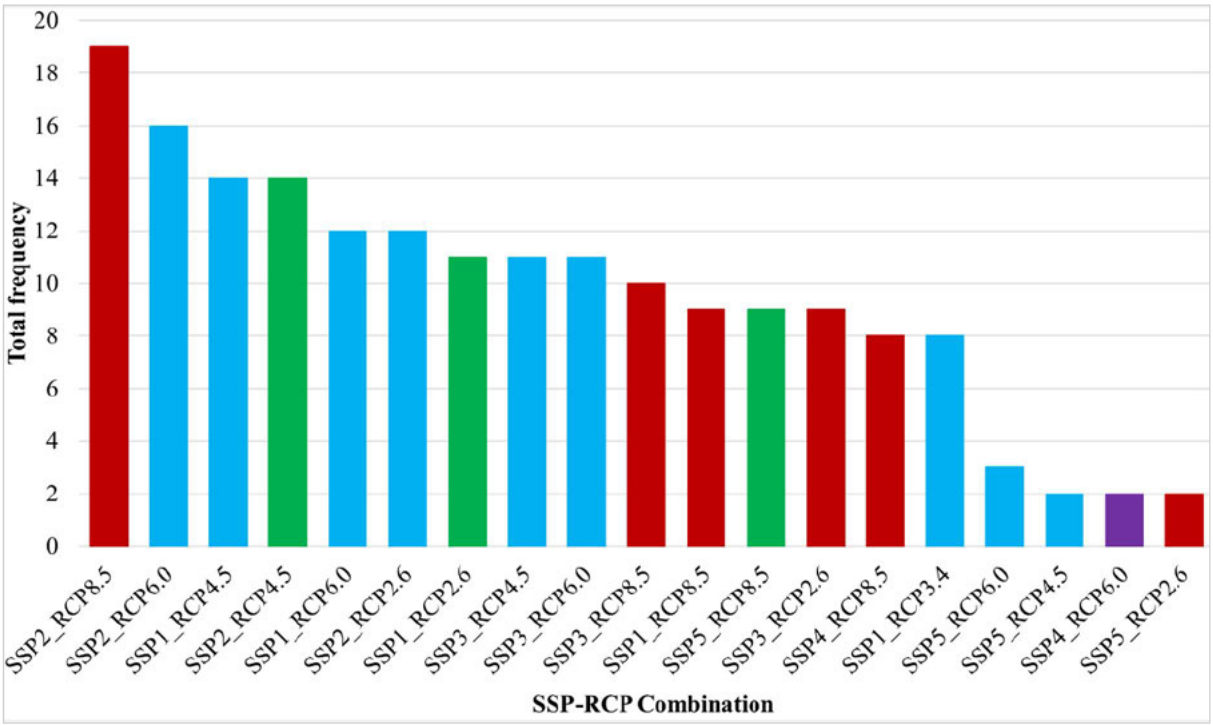


Figure 6.7: Frequency of integrations of pre-CMIP5 and CMIP5 socio-economic and climate pathways in WEF nexus scenario planning and RAPs studies (All = CMIP5 SSP-RCP integrations by previous studies; Green = also correspond to CMIP6 Tier 1 scenarios of top priority; Purple = also correspond to CMIP6 Tier 2 additional scenarios of interest; Red = unlikely CMIP5 SSP-RCP combinations; Blue = other pre-CMIP5 and CMIP5 socio-economic and climate combinations (O'Neill *et al.*, 2020; World Bank, n.d.))

According to O'Neill *et al.* (2020), the climate (RCPs) and societal (SSPs) future pathways should be integrated with caution on the plausibility, coherence, consistency and feasibility of particular combinations of SSPs and RCPs. Similarly, according to World Bank (n.d.), not all possible combinations of SSPs and RCPs are viable and feasible. For example, O'Neill *et al.* (2020) and World Bank (n.d.) emphasize that SSP1, SSP2, SSP3 and SSP4 are unlikely with RCP8.5, the latter which can only be achieved under SSP5. On the other hand, pathways of stricter climate policy and strong mitigation (e.g., RCP1.9 and RCP2.6) are not achievable under SSP3 and fossil-fuelled high emissions SSP5 (O'Neill *et al.*, 2020; World Bank, n.d.). This may imply that at least 31% of previous WEF nexus scenario planning studies that integrated SSPs and RCPs misaligned the likely evolutions of future climate and socio-economic conditions (O'Neill *et al.*, 2020; World Bank, n.d.). Only four of the CMIP5 SSP-RCP pairs by author integration coincide with some of the latest eight CMIP6 scenarios of top priority (Tier 1: SSP2-RCP4.5, SSP1-RCP2.6, SSP5-RCP8.5) and those of interest (Tier 2:

CMIP5 SSP4-RCP6.0) (Figure 6.7) (O'Neill *et al.*, 2016; Tebaldi *et al.*, 2021). de Vos *et al.* (2021) predicted increases in future global consumption and withdrawal demands and irrigated areas (in other regions) to ascend from SSP1-RCP4.5 through SSP2-RCP6.0 to SSP3-RCP6.0 by 2070. The same trend was predicted for global total water withdrawal from SSP1-RCP3.4 (12%) through SSP2-RCP4.5 (26%) to SSP3-RCP 4.5 (29%) during 2010–2050 (Bijl *et al.*, 2018). In the Mekong River basin, decreases in gross hydropower potential and production and irrigation water supply for rice will be higher under SSP2-RCP6.0 than SSP2-RCP2.6 (Meng *et al.*, 2021). In the Indus basin, higher increases in water, energy and food resource requirements are expected under the SSP1-RCP4.5 scenario, followed by SSP2-RCP6.0 and SSP3-RCP8.5 during 2030-2080. In the same basin under the SSP2-RCP6.0 pathways, Vinca *et al.* (2021) predicted a fourfold increase in electricity demand and GHG emissions, a 45% rise in demand for agricultural products, a 22% increase in water withdrawals, a one third increase in water demand, and a doubling of water stress by 2050 compared relative to 2020.

6.3.2.2.1.3 Post-CMIP5 socioeconomic and climate change pathways (CMIP6 SSP-RCP) in WEF nexus scenario planning

For CMIP6, each SSP drives a corresponding future projection of GHG emissions and land-use change under the baseline SSP storyline, with higher values representing stronger climate warming effects. CMIP6 SSPs represent possible societal development and policy paths for meeting designated radiative forcing by 2100, and the scenarios are named by the acronym SSPX-Y wherein ‘X’ is the baseline SSP scenario, and ‘Y’ refers to the RCP radiative forcing levels. Generally, the CMIP6 SSPX-Y scenarios are categorised into Tier 1 of top priority (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) and Tier 2 of interest (SSP1-1.9, SSP4-3.4, SSP5-3.4 OS, SSP4-6.0), all whose detailed attributes are available in Appendix M and the founding publications (O'Neill *et al.*, 2016; Abram *et al.*, 2019; Gidden *et al.*, 2019; Meinshausen *et al.*, 2020; IPCC, 2021). When this work was completed (last search on 10 January 2023), only one WEF nexus scenario planning study in the Mekong River delta had used CMIP6 SSPX-Y scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5 to assess the impact of climate and socioeconomic changes on rice yield, power generation and water withdrawal in Vietnam (Wang *et al.*, 2021). They predicted descending increases in water withdrawals (total, coal-fired power generation), from SSP5–8.5 (high forcing and a high challenge to mitigation and adaptation), through SSP4–6.0 (medium-forcing pathways with a high

challenge to adaptation), SSP2–4.5 (middle-of-the-road pathway with intermediate challenges for mitigation and forcing signal), SSP3–7.0 (medium-high future mitigation and forcing pathways), to SSP1–2.6 (low societal vulnerability and forcing level) by 2050 (Appendix M) (Wang *et al.*, 2021). On the other hand, the Sustainability Index descended from SSP1–2.6 (0.58), through SSP3–7.0 (0.55), SSP2–4.5 (0.48), SSP4–6.0 (0.42), to SSP5–8.5 (0.33) (Wang *et al.*, 2021). Gao *et al.* (2024) provided a recent review of methods for investigating climate change impacts on the WEF nexus. Thus, climate change and socio-economic pathways, especially the globally established and updated RCPs and SSPs (e.g., CMIP6 SSPX-Y), are a key component in people-centred and data-informed methodological frameworks and guidelines for co-developing integrated WEF nexus scenarios.

6.3.2.2.2 Pathways based on interventions to manage supply and demand of WEF resources for WEF nexus scenario planning

Over and above the established pathways of change such as RCPs and SSPs, WEF nexus studies tend to include intervention-based pathways when planning their scenarios (Johnson and Karlberg, 2017; Kulat *et al.*, 2019), although typically less consideration is given to the demand-side developments compared to the supply-side (Hoolohan *et al.*, 2019). These pathways seek to understand and highlight the impacts of certain interventions, policies, developments and adaptive strategies on linkages between nexus components, as well as the associated evolution in resource supply and demand in alternative futures (Karlberg *et al.*, 2015; Dhaubanjar *et al.*, 2017; Ravar *et al.*, 2020). Such interventions are here categorised and analysed as either cross-cutting or by the specific sectors in which they are intended to affect resource production, generation, supply, use and consumption.

6.3.2.2.2.1 Cross-cutting interventions used in WEF nexus scenario planning studies

The major cross-cutting interventions and measures that were considered in previous WEF nexus scenario planning studies can be categorized into (i) policy, (ii) climate change, (iii) economic and financial, (iv) international cooperation, (v) resources management, (vi)

technology, (vii) industry, (viii) transport, (ix) environmental/ecosystem, (x) land use, and (xi) awareness and capacity building (Table 6.5).

Table 6.5: Cross-cutting interventions considered in WEF nexus scenario planning studies

Cross-cutting interventions considered in WEF nexus scenario planning studies

Interventions	Measures
Policy	Policy and governance framework • Changes • Alignment, supportiveness • Diversity and density • Level of implementation
Climate change	Adaptation to impacts • Mitigation policies • Carbon price policy • Greenhouse gas (GHG) emissions constraints • Decrease in livestock farming
Economic and financial	Micro-credit • Taxation • Alternative source of income for farmers • Markets • Minimization of the cost and maximization of returns
International cooperation	Level of international coordination • Trade and market liberalization • Intraregional instruments and intersectoral collaboration • Levels of transboundary sharing
Resources management	Raw material use reduction • Recycling • Specific household enhancement
Technology	Advancement • Innovation • Infrastructure
Industry	Processes and products • Agro-industry • Industrial structure
Transport	Electric • Inland waterway • Rail for freight • Pipeline • High-speed ground • Bioelectric ferries • Wind-assisted container vessels • Bikes • E-bikes • Car clubs
Environmental / ecosystem	Prioritizing environmental (ecological) flows • Flood pulse and flow regimes • Reduction in flood risk • Restoration of degraded ecosystems • Green infrastructure • Reducing manure and fertilizer use • Carbon footprint intensity • Emissions trading system • Ecological civilization • Conservancy projects • Reforestation • Carbon capture and soil carbon sequestration • Reduce pollution • Land management for reducing emissions of GHGs (methane) and nitrogen • Green roof
Land use	Vertical settlements • Agricultural land area • Urbanization
Awareness and capacity building	Perception and behaviour change • Public will adjustment • Lifestyle changes

Source: Author's synthesis of literature cited in the succeeding five paragraphs

The national, regional and international policy and governance frameworks included plans, strategies, visions, goals, programs, directives, commitments, and standards for sectors (water, energy, food/agriculture, sectoral planning, population control), growth, transformation, climate action, green economy, economic development, poverty reduction, and clean development (Karlberg *et al.*, 2015; Lechón *et al.*, 2018; Karabulut *et al.*, 2019). Consideration was also given to policies on infrastructure development and their level of implementation (Basheer *et al.*, 2018; Terrapon-Pfaff *et al.*, 2021). Pathways on the level of policy implementation included poor/weak/pessimistic and firm/full/optimistic (Keskinen *et al.*, 2015; Johnson and Karlberg, 2017; Karim and Daher, 2021). Other studies factored in regional and international policy frameworks on climate mitigation, including nationally determined contributions (NDCs), unconditional commitments and sustainable development goals (SDGs)

(Borgomeo *et al.*, 2018; Miralles-Wilhelm *et al.*, 2018; Niva *et al.*, 2020). A particular policy consideration was China's "two-child" policy for population control (Jin *et al.*, 2019).

Economic interventions included high resource pricing and taxation on fossil fuels, and micro-credit facilities for resource-saving and efficient consumption, as well as promoting the uptake of and transition from non-renewable energy and fossil fuels to renewable and clean efficient technologies such as modern fuels for cooking and heating for the resource-poor households (van Vuuren *et al.*, 2015; Ringler *et al.*, 2016). Other economic measures included increasing agro-industrial development to add the value of agricultural products and stimulate a balanced growth of the industrial and agricultural sectors (Purwanto *et al.*, 2021a), as well as creating an alternative source of income for farmers towards low water-consumption rural industries (Ghafoori-Kharanagh *et al.*, 2021).

For international cooperation, the levels of transboundary sharing included unilateral action, coordination (sharing flow and trade information) and collaboration (regional cooperation), accompanied by different extents of economic benefits maximization, resource consumption planning, product trade, regional product (electricity, food) trade market, and sharing of river discharge predictions (Basheer *et al.*, 2018; Wada *et al.*, 2019; Vinca *et al.*, 2021). Interesting pathways that were considered include the trade friction between China and the United States of America (USA), as well as the process of departure of the United Kingdom (UK) from the European Union (EU), known as Brexit (Ziv *et al.*, 2018; Jin *et al.*, 2019). For the Brexit process, the considered pathways were amicable transition, simple separation, hostile divorce, and clean break (Ziv *et al.*, 2018).

Pathways for resource use included strength/intensity of resource management (weak, medium, strict) and growth of resource utilization efficiency (slow, efficient, improved) (Xue *et al.*, 2018; Chen and Xu, 2021; Wen *et al.*, 2022). For technology, interventions included progress in innovation, for example, in the industry and manufacturing sector, innovation of operation and maintenance technology, green lighting, and intelligent water metering (Xue *et al.*, 2018; Sun *et al.*, 2021). Technological interventions at the household level included multi-utility services, urine separation technology (urine-diverting toilets), pyrolysis of separated sewage sludge, algae production in wastewater treatment facilities, consolidation and co-treatment of household organic waste at the household level (e.g., food grinders) (Walker *et al.*, 2017; Hoolohan *et al.*, 2019; Kolusu *et al.*, 2021).

Measures for land use included vertical settlements to save agricultural land, the establishment of young forests, and decreasing meadow and pasture area (Zhao *et al.*, 2018; Purwanto *et al.*, 2021a; Sušnik *et al.*, 2021). The consideration of protected areas is expected to enhance future co-benefits between hydropower and irrigation in the Mekong River basin, more so under the 2°C global warming scenario compared to 1.5°C global warming (Meng *et al.*, 2021). Information campaigns were considered for the public will adjustment and educating people on efficient resource consumption, resource-saving appliances, sustainable behaviour and resource curtailment/saving habits (Larkin *et al.*, 2020; Terrapon-Pfaff *et al.*, 2021; Wang *et al.*, 2021). Examples of media channels for these measures include newspapers, television (TV) advertisements, and posters (Casazza *et al.*, 2021). The choice of pathways of cross-cutting interventions depend on context and they capture resource use and management in shaping people-centred WEF nexus futures.

6.3.2.2.2.2 Water sector interventions used in WEF nexus scenario planning studies

The major water sector interventions and measures that were considered in previous WEF nexus scenario planning studies include (i) augmenting and diversifying supply, (ii) nonconventional water supplies, (iii) improving water allocation, (iv) increasing water-use efficiency in all sectors, (v) irrigation and agricultural water management, (vi) policy and regulation, and (vii) water resources protection (Table 6.6).

Table 6.6: Water sector interventions considered in WEF nexus scenario planning studies

Water sector interventions considered in WEF nexus scenario planning studies

Interventions	Measures
Augment and diversify supply	Expand surface water storage and diversion • Groundwater extraction • Rainwater harvesting • Water transfers
Nonconventional water supplies	Wastewater treatment, recycling and reuse • Desalination • Irrigation tailwater (drainage) • Controlled blending and dilution
Improve water allocation	Across sectors • Dam operation (filling, release) rules • Free water to indigent households and farmers • Minimization of freshwater abstraction
Increase water-use efficiency in all sectors	Reduce water losses in distribution (supply) network and irrigation • In urban households and the tourism sector • Less water-intensive electricity generation
Irrigation and agricultural water management	With or without expansion of irrigation area • Monitoring agricultural water use • Irrigation scheduling • Shift to crops that use less water (e.g., arboriculture, dry land crops) • Efficient precision technologies • Soil moisture monitoring
Policy and regulation	Proactive and conservation-oriented water charges • Water trade • Regulate water access • Water quota • Wastewater use standards • Water pricing and taxation • International obligations
Water resources protection	Catchment management • Control water (e.g., groundwater) withdrawals • Reduce diffuse pollution

Source: Author's synthesis of literature cited in the succeeding four paragraphs

Measures for expanding water supply included resizing existing or constructing new multipurpose surface water storage infrastructure such as dams (large, medium, and small) and water diversion structures (Stamou and Rutschmann, 2018; Geressu *et al.*, 2020; Ogbolumani and Nwulu, 2021). Techniques for resizing existing dams included increasing their height and lowering their stream bottoms by dredging the channel (Sishodia *et al.*, 2018). Water harvesting and storage techniques included dispersed ponds (percolation, wet detention, infiltration) and cistern storage (Sishodia *et al.*, 2017; Valencia *et al.*, 2022). For non-conventional water supplies, the wastewater treatment technologies were the intermittent sand filter, trickling filter, moving bed biofilm reactor, rotating biological contractors, membrane bioreactor, extended aeration, sequencing batch reactor, multi-stage flash, reverse osmosis, and irrigation tailwater treatment technology (Daher and Mohtar, 2015; Namany *et al.*, 2019; Ramirez *et al.*, 2021).

For increasing water-use efficiency, specific measures included reducing non-revenue water and using irrigation systems that have high efficiency in pumping, conveyance and application, for example, drip, bubbler and sprinkler irrigation systems (Naderi *et al.*, 2021; Nasrollahi *et al.*, 2021; Terrapon-Pfaff *et al.*, 2021). Related measures included improved management and stronger enforced regulations in smallholder irrigation towards reducing losses by evaporative conveyance, weed transpiration, evaporation, nonrecoverable return flows, and irrigation return flows (Geressu *et al.*, 2020). Techniques for monitoring agricultural water use and

productivity included earth observation and remote sensing (Borgomeo *et al.*, 2018; Miralles-Wilhelm *et al.*, 2018). Measures for saving water in electricity generation included phasing out water-intensive cooling technologies, e.g., once through for thermal power generation, and replacing them with less water-intensive seawater recirculation technologies or wet/dry hybrid or electricity generation technologies that use little or no water or dry (air) cooling (Borgomeo *et al.*, 2018; Kulat *et al.*, 2019; Terrapon-Pfaff *et al.*, 2021). Similar interventions included reducing cleaning water consumption in power generation plants by using waterless cleaning technologies, which are also applicable in industry and manufacturing (Hoolohan *et al.*, 2018; Larkin *et al.*, 2020). Specific water-saving measures at the household level included retrofitting buildings with water-saving shower facilities, and water-saving appliances, reducing the average daily washing length and shower frequency, and using waterless technologies, e.g., for cleaning (Xue *et al.*, 2018; Casazza *et al.*, 2021; Terrapon-Pfaff *et al.*, 2021).

Agricultural water management interventions were intended to increase on-farm water use efficiency and productivity by training farmers on water-saving practices such as irrigation scheduling (Borgomeo *et al.*, 2018; Maraseni *et al.*, 2021). Renewable energy was considered for treatment processes such as desalination and moving water with solar pumps for irrigation (Miralles-Wilhelm *et al.*, 2018; Degirmencioglu *et al.*, 2019). Pricing interventions were targeted for raw water withdrawal, such as irrigation (Bieber *et al.*, 2018; Ramirez *et al.*, 2021). Water resource protection measures to enhance water quantity and quality included controlling wastewater return flow recharge and improving water infrastructure and management (Martinez *et al.*, 2018; Bakhshianlamouki *et al.*, 2020; Chen and Xu, 2021). Xue *et al.* (2018) considered implementing standards for the minimum discharge from cooling systems in thermal power.

At a global level for the period 2010–2050, Bijl *et al.* (2018) found water allocation mechanisms (i.e., priority rules for irrigation vs. non-agricultural) to significantly reduce water deficits compared to water use efficiency improvements and limiting irrigation expansion. Thus, the choice of pathways based on interventions for managing supply and demand of water resources depend on context and they are crucial in exploring people-centred WEF nexus futures. However, the water sector can adopt and adapt the RAPs methodology for downscaling and extending global pathways (SSPs and RCPs) to provide the additional details needed to implement regional and local assessments in WEF nexus scenario planning.

6.3.2.2.2.3 Energy sector interventions used in WEF nexus scenario planning studies

The major energy sector interventions and measures that were considered in previous WEF nexus scenario planning studies include (i) transition, transformation and augmenting supply, (ii) decentralized generation, (iii) renewable and carbon-free energy, (iv) non-renewable energy, (v) improved supply efficiency, (vi) improved end-use efficiency, and (vii) policy and regulation (Table 6.7).

Table 6.7: Energy sector interventions considered in WEF nexus scenario planning studies

Energy sector interventions considered in WEF nexus scenario planning studies

Interventions	Measures
Transition, transformation, and augment supply	Diversification of energy mix (different energy carriers) • Grid expansion • Retirement of coal, nuclear, and fossil fuels towards renewable energy • Gas-fired electric power generation plants • Renewing coal-fired generation plants •
Decentralized generation	Local energy production
Renewable and carbon-free energy	Biofuel (biodiesel, bioethanol) • Solar • Wind (on and offshore) • Geothermal • Marine • Hydropower • Biomass (e.g., straw) • Hydrogen (H_2)
Non-renewable energy	Fossil fuel with carbon-capture-and-storage • Pulverised coal • Nuclear • Liquefied petroleum gas (LPG) • Natural gas • Hydrogen (H_2) • Flue gas desulfurization
Improved supply efficiency	Conversion (generation) efficiency • Transmission and distribution • Waste heat recycling • Power plants thermal efficiency • Increased efficiencies in grain production, oil and gas exploitation
Improved end-use efficiency	Energy-smart and less energy-intensive goods and appliances • Insulation • Glazing • Heat networks • Continuous monitoring and cyber security • Water pumps
Policy and regulation	High energy (fuel, electricity) price • Trade (export, import) • Carbon credit price • Taxes (fossil fuel, carbon) • Subsidies for renewables and clean energy • Subsidies for non-renewables • Energy trade market • Reducing fossil fuel imports • Tariff on electricity imports • Feed-in electricity tariffs • Energy consumption structure

Source: Author's synthesis of literature cited in the succeeding paragraph

Specific measures for increasing energy production included investing in infrastructure such as resizing and construction of hydropower plants (e.g., large, moderate, small, run-of-river), power grid and transmission lines (Amjath-Babu *et al.*, 2019; Dhaubanjar *et al.*, 2021; Siderius *et al.*, 2021). For power cogeneration units, pathways are considered for internal combustion engines, fuel cells, microturbines, and stirling engines (Cansino-Loeza and Ponce-Ortega, 2021). For a just energy transition that is inclusive of rural and resource-poor households, there was consideration for decentralized local energy production, electrification, modern cooking stoves (e.g., improved efficient biomass-fuelled gasifier), and clean-burning fuels such as liquefied petroleum gas (LPG), biogas, biomass pellets (Karlberg *et al.*, 2015; van Vuuren *et*

al., 2015; Sušnik *et al.*, 2021). The technology for bioenergy production included anaerobic biogas digesters (Abdel-Aal *et al.*, 2020), while the sources of bioenergy included biomass (miscanthus, algae), sugarcane, corn, waste, sewerage, rape, canola, and wheat (Walsh *et al.*, 2016; Schwanitz *et al.*, 2017; Xue *et al.*, 2018). Regulatory interventions included restriction of biomass use for fodder and fuel (Johnson and Karlberg, 2017). Thus, the choice of pathways of interventions for managing the supply and demand of energy resources depend on context and they are crucial in exploring people-centred WEF nexus futures. However, the energy sector can adopt and adapt the RAPs methodology for downscaling and extending global pathways (SSPs and RCPs) to provide the additional details needed to implement regional and local assessments in WEF nexus scenario planning.

6.3.2.2.2.4 Food sector interventions used in WEF nexus scenario planning studies

The major food sector interventions and measures that were considered in previous WEF nexus scenario planning studies included (i) increased agriculture yields and productivity, (ii) good agricultural practices, (iii) agricultural land expansion, (iv) policy and regulation, (v) irrigation, (vi) improved efficiency, (vii) changing diet, lifestyle, and consumption patterns, and (viii) alternative foods (Table 6.8).

Table 6.8: Food sector interventions considered in WEF nexus scenario planning studies

Food sector interventions considered in WEF nexus scenario planning studies

Interventions	Measures
Increase agriculture yields and productivity	Intensive agriculture and commercialisation • Agricultural technologies and mechanization • Local food production • Genetically modified crops • Precision farming • Diversified food production
Good agricultural practices	Ecological (green) agriculture • Precision agriculture • Improved efficient use of inputs (e.g., fertilizer, pesticides) • Manure recycling • Crop rotation • Fallowing • Crop choice and cropping patterns • Land and water management • Organic farming • Reduced tillage • Green cultivation development • Smart agriculture
Agricultural land expansion	Rainfed • Irrigated
Policy and regulation	Regulate equitable access to food • Trade (import, export) • Food prices • Food safety and quality programs • Redistribution of surplus food • Agricultural subsidies
Irrigation	Prioritize water for irrigated agriculture • Full or supplemental irrigation
Improve efficiency	Feed • Reduce food waste • Circular economy
Change diet, lifestyle, and consumption patterns	Intake of macro-nutrients (proteins, calories, and fats)
Alternative foods	From algal biomass • Nutraceuticals (meal pills) and synthetic proteins • Insect protein • Ready meals • Highly processed format foods • Commodity food products from algal biomass grown in salt water on non-arable land

Source: Author's synthesis of literature cited in the succeeding paragraph

Specific measures included prioritizing the production of food crops, livestock and fish in agriculture, augmenting green water use (rainfed) with blue water (irrigation), mixed cultivation (rainfed, irrigated), dry-season production, and subsidizing irrigation through 'collective' networks (Bazzana *et al.*, 2020; Payet-Burin *et al.*, 2021; Ramirez *et al.*, 2021). Technological interventions included climate-controlled food production (greenhouses), novel agricultural systems (hydroponic, aquaponics, vertical farming), new-tech irrigation systems, global positioning system (GPS)-guided tractors, robotics, sensors, improved storage and transport of produce (Martinez *et al.*, 2018; Toboso-Chavero *et al.*, 2019; Maraseni *et al.*, 2021). Interventions with a similar focus included restoration agriculture, planting drought-tolerant crop varieties, local production of food crops, and renewable energy-powered processing and value addition (Bremer *et al.*, 2018; Yan *et al.*, 2018; Ghafoori-Kharanagh *et al.*, 2021). Other measures included diversifying foods with substitutes, reducing losses in food supply chains, and using on-site disposal systems (van Vuuren *et al.*, 2015; Damerau *et al.*, 2016; Bremer *et al.*, 2018). For replacement foods, examples included ready meals (takeaways, meals-on-the-go, shakes, meal kits) and highly processed format foods (e.g., powdered foods and meal pills) (Hoolohan *et al.*, 2019; Larkin *et al.*, 2020).

6.3.2.2.2.4.1 Consideration of RAPs in WEF nexus scenario planning

Unlike the water and energy sectors, the agriculture community established methodology for developing RAPs that extend global pathways (CMIP5 SSPs and RCPs) to provide the additional biophysical, socioeconomic and management detail of projected plausible futures needed to implement integrated global and regional assessments of climate change impacts and adaptation on agricultural systems (Valdivia *et al.*, 2015; Antle *et al.*, 2017; Mu *et al.*, 2019). RAPs studies tend to consider three likely conditions namely optimistic (sustainable development), business-as-usual (BAU) and pessimistic (dysfunctional world) pathways, which are used to drive crop, livestock/pastures, land-use and economic models in impact assessments. Detailed information on RAPs, including their pathway descriptions and matrices of synergies and trade-offs, is available in the founding publications (Valdivia *et al.*, 2015; Antle and Valdivia, 2016; Rosenzweig *et al.*, 2016). However, the evolution of agricultural (crop and livestock production) systems was included in WEF nexus scenario planning as interventions without categorically and explicitly using established pathways such as RAPs. Similarly, RAPs are more agricultural production-centric than food and do not explicitly integrate the water and energy food sectors and linkages. Thus, cross-cutting and sectoral (e.g., water, energy, food) intervention-based pathways such as RAPs, if co-explored with stakeholders including the communities in the case studies, are a key component in exploring people-centred integrated WEF nexus futures.

6.3.2.2.2.5 Integrating interventions in WEF nexus scenarios

Integrating interventions in WEF nexus scenarios is contextual and can accrue multiple benefits and address trade-offs. At global level, implementing climate policies and other responses at half their potential, including higher agricultural yields, dietary changes and reduction of food waste, may generally improve food production, energy generation, water consumption, agricultural area, and GHG emissions, compared to pathways and scenarios of individual responses and 'no policy' (van Vuuren *et al.*, 2019). Yang *et al.* (2018) found that dams can mitigate the negative impacts of climate change on hydropower generation and ecosystem health in the Niger River Basin. However, given the large number of scenarios that can be obtained from combining the probable pathways of socioeconomic change, climate change and

interventions, against the restrictions in time and computations, it is recommended to narrow down to a small number of particularly relevant scenarios, based on broad plausible storylines/narratives that reflect major possibilities from which sufficient recommendations can be drawn (Johnson and Karlberg, 2017; Kulat *et al.*, 2019).

6.3.2.3 Scales and analytic tools in WEF nexus scenario planning

The planning of WEF nexus scenarios at medium spatial scales dominated (52%) the reviewed studies, with large (31%) and local scale studies (17%) sharing the other half (Figure 6.8a). This shows a critical gap in WEF nexus scenario planning at local scales (e.g., household to district) where challenges are felt and interventions are actionable (Casazza *et al.*, 2021; de Vos *et al.*, 2021).

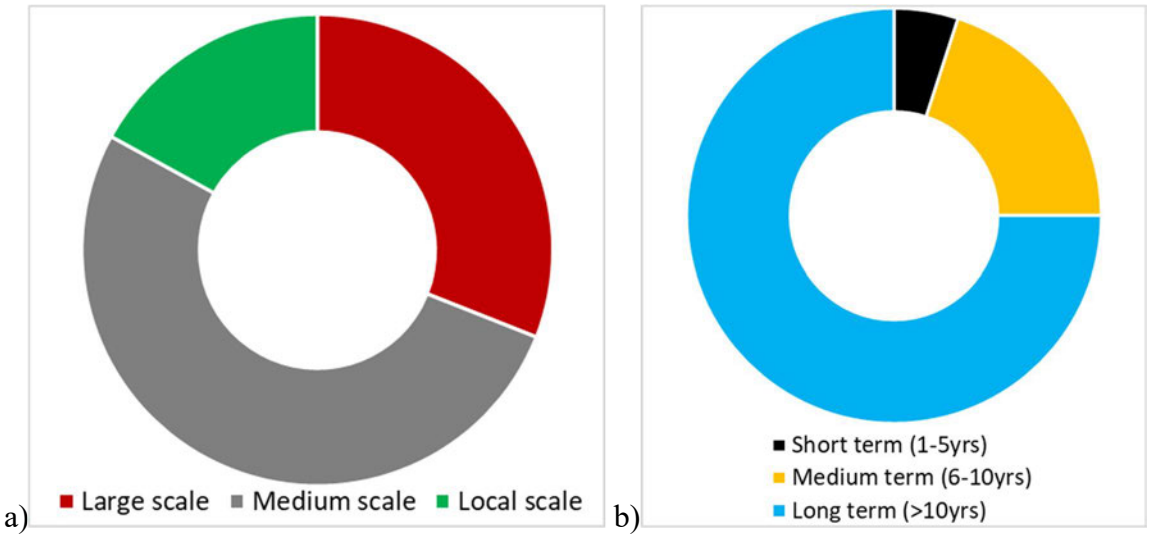


Figure 6.8: (a) Spatial and (b) temporal scales in WEF nexus scenario planning

Concerning the temporal scale, long-term planning horizons dominate (75%), followed by medium-term horizons (20%) and short-term horizons (5%) (Figure 6.8b). The consideration and dominance of long-term planning horizons in WEF nexus scenario planning is favourable for exploring future probable WEF systems towards the realisation of some promises of the WEF nexus approach: addressing and achieving long-term sustainability challenges and goals, respectively (Naidoo *et al.*, 2021; Adom *et al.*, 2022; Salem *et al.*, 2022). Short- and medium-term interventions also have long-term consequences that must be accounted for (Cremades *et*

al., 2019). Thus, planners need to carefully consider the spatial and temporal of their WEF nexus scenarios.

6.3.2.3.1 Analytic tools for WEF nexus scenario planning at different spatial scales

Exploratory modelling of WEF nexus scenarios uses computational experiments to ask "what if" questions that unpack implications of different assumptions and hypotheses about future trends on multidimensional outcomes of interest to researchers, societies and policy makers to inform and support sustainable decision-making (Borgomeo *et al.*, 2018). It involves computational modelling through simulation and optimization that quantifies spatial and temporal interactions and interconnections, processes and feedback within the WEF nexus (Bieber *et al.*, 2018). Several analytic tools have been used to plan WEF nexus scenarios and analyse their results across different spatial scales, from local through medium to large scales (Table 6.9).

Table 6.9: Summary of some analytical tools that were applied at various spatial resolutions for WEF nexus scenario planning

Spatial scale	Model applied	Category
Local	Soil and Water Assessment Tool (SWAT), Lund-Potsdam-Jena model (LPJmL),	Hydrological model
	DSSAT, AquaCrop, Global Agro-Ecological Zones (GAEZ)	Crop model
	WEF (water-energy-food) model, Food-Energy-Water Calculator (FEWCalc), City Geography Markup Language (CityGML), MuSIASEM, (Participatory) System Dynamics Modelling (SDM)	WEF nexus model
Medium	Soil and Water Integrated Model (SWIM), Vmod, MIKE SHE/MIKE, SWAT, and HYMOD_DS	Hydrological model
	CROPWAT, CLIMWAT, AquaCrop, and DSSAT	Crop model
	Water Evaluation And Planning system (WEAP)-Low Emissions Analysis Platform (LEAP), WEF Nexus Tool 2.0, Common Agricultural Policy Regionalised Impact (CAPRI), Q-Nexus, Open Source energy MOdelling SYStem (OSeMOSYS), Regional Environmental Assessment Tool for Food-Energy-Water nexus (GREAT for FEW), Urban Circular Economy Calculator (UCEC), WEFSiM, Agricultural Water-Energy-Food Sustainable Management (AWEFSM), Energy Portfolio Assessment Tool (EPAT), (Participatory) System Dynamics Modeling (SDM)	WEF nexus model
Large	Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) and RiverWare, SWAT, LPJmL, Spatial Processes in Hydrology (SPHY), Vmod, and Integrated Catchment Model (INCA)	Hydrological model
	CROPWAT, DSSAT, GAEZ, Global Crop Water Model (GCWM)	Crop model
	Nexus Webs, Nexus Solutions Tool (NEST), Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF), Decision-Analytic Framework to explore the water-energy-food NExus (DAFNE), (Participatory) System Dynamics Modeling (SDM)	WEF Nexus model

These tools utilize, among others, mathematical principles on provided inputs to qualify and quantify spatial and temporal evolution of the WEF nexus and provide indicators and indices which can be visualised quantitatively, graphically and spatially (Bijl *et al.*, 2018). They include Integrated Assessment Models (IAMs) and frameworks that test classical "what if" questions in dialogue with stakeholders, in exploring how the water, food and energy systems may develop in the future, and the relevant synergies and trade-offs between these systems and possible response strategies to shortages (Johnson and Karlberg, 2017; de Vos *et al.*, 2021; Sušnik *et al.*, 2021; Terrapon-Pfaff *et al.*, 2021). They are an opportunity to shift away from

previous efforts that tended to slant towards individual silos and disciplines (Bijl *et al.*, 2018). Readers are referred to background publications on sectoral analytic modelling tools. The same applies to the WEF nexus analytic modelling tools, some of whose key characteristics were discussed in several reviews such as by Taguta *et al.* (2022). Thus, scales and analytical tools are integral components in co-developing people-centred and data-informed integrated WEF nexus scenarios.

6.3.2.4 Summary on WEF nexus scenario planning

Scenario planning has been applied in the WEF nexus approach, considering major drivers of change and pathways, including climate change, socioeconomic conditions, and the environment. The process involves comparing the impacts of different climate and socioeconomic change projections, resource management policies or actions on the physical/economic system being modelled (Voinov and Bousquet, 2010; Hoolohan *et al.*, 2019). Comparison is made between (i) a reference scenario that excludes the feature and (ii) an alternative scenario(s) that include(s) the feature (or combination of features) such as policy (e.g., mitigation or adaptation), an alternative assumption about a driver (e.g., population growth or effectiveness of governance), or a climate change impact (e.g., climate effects on crop yield) (O'Neill *et al.*, 2020). However, majority of WEF nexus scenario planning studies neglect stakeholders and their individual preferences, while some are selective on the type of stakeholders which potentially leads to bias and exclusion of knowledge in WEF nexus futures. Similarly, there is a general lack of methodological frameworks and guidelines, especially those that focus on the people and not resources only. The latest CMIP6 SSP-RCP (2016) pathways received little attention and consideration in WEF nexus scenario planning. Although RAPs are compatible with SSPs and RCPs, WEF nexus scenario planning studies did not use RAPs to represent the evolution of agricultural systems, nor do RAPs explicitly capture the entirety of WEF nexus interconnections. This impedes visioning future agricultural development pathways within the WEF nexus approach. These gaps undermine quality, saliency, credibility, relevance, legitimacy, and acceptability of WEF nexus scenarios

Closing these gaps requires participatory WEF nexus scenario planning that integrates qualitative and quantitative exploration of potential future WEF system developments in conjunction with stakeholders, going beyond technical aspects to include social, economic and

political concerns (Star *et al.*, 2016; Johnson and Karlberg, 2017; Newman *et al.*, 2024). A starting point would be to develop people-centred and data-informed methodological frameworks and guidelines for co-developing integrated WEF nexus scenarios. Application of such methodological frameworks and guidelines will need to consider the updated CMIP6 SSPX-Y pathways as well as the RAPs.

The major cross-cutting interventions that were considered in previous WEF nexus scenario planning studies included (i) policy, (ii) climate change, (iii) economic and financial, (iv) international cooperation, (v) resources management, (vi) technology, (vii) industry, (viii) transport, (ix) environmental/ecosystem, (x) land use, and (xi) awareness and capacity building. The major water sector interventions and measures included (i) augmenting and diversifying supply, (ii) nonconventional water supplies, (iii) improving water allocation, (iv) increasing water-use efficiency in all sectors, (v) irrigation and agricultural water management, (vi) policy and regulation, and (vii) water resources protection. The main energy sector interventions and measures included (i) transition, transformation, and augmenting supply, (ii) decentralized generation, (iii) renewable and carbon-free energy, (iv) non-renewable energy, (v) improved efficiency (supply and end-use), and (vi) policy and regulation. The key food sector interventions and measures included (i) increasing agriculture yields and productivity, (ii) good agricultural practices, (iii) agricultural land expansion, (iv) policy and regulation, (v) irrigation, (vi) improving efficiency, (vii) changing diet, lifestyle, and consumption patterns, and (viii) alternative foods. Long-term planning horizons (>10yrs) dominated in WEF nexus scenario planning, which is desirable for planning sustainable development, medium-large spatial scales dominated and left a gap for local scales. At the same time, an array of sectoral and integrated analytic tools (IAMs) was used for modelling WEF nexus scenarios.

6.3.3 Proposing a generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios

A minority of WEF nexus scenario planning studies explicitly reported engagement of stakeholders (28%) (Figure 6.4a), as well as people-centred methodological frameworks (13%) (Figure 6.3a) and guidelines (20%) (Figure 6.3b). This lack of a scenario planning framework and guideline blueprints for the WEF nexus community of researchers and practitioners

compromises robustness, rigour, and utility. Some studies on WEF nexus scenario planning and RAPs development provided methodological framework and guidelines, although they differ widely in their structure, content, steps/procedures and logic (Rosenzweig *et al.*, 2016; Daher *et al.*, 2017; Cremades *et al.*, 2019; Marttunen *et al.*, 2019; Wada *et al.*, 2019; González-Rosell *et al.*, 2020; Tumbo *et al.*, 2020; Terrapon-Pfaff *et al.*, 2021).

6.3.3.1 A generic people-centred and data-informed methodological framework for co-developing integrated WEF nexus scenarios

To bridge the aforementioned gaps in people-centred and data-informed methodological frameworks for WEF nexus scenario planning, this section uses existing frameworks as foundation as well as some key elements of WEF nexus scenario planning from literature for enrichment, in the McMeekin *et al.* (2020) methodology, to develop a generic people-centred and data-informed methodological framework for co-developing integrated WEF nexus scenarios (Figure 6.9).

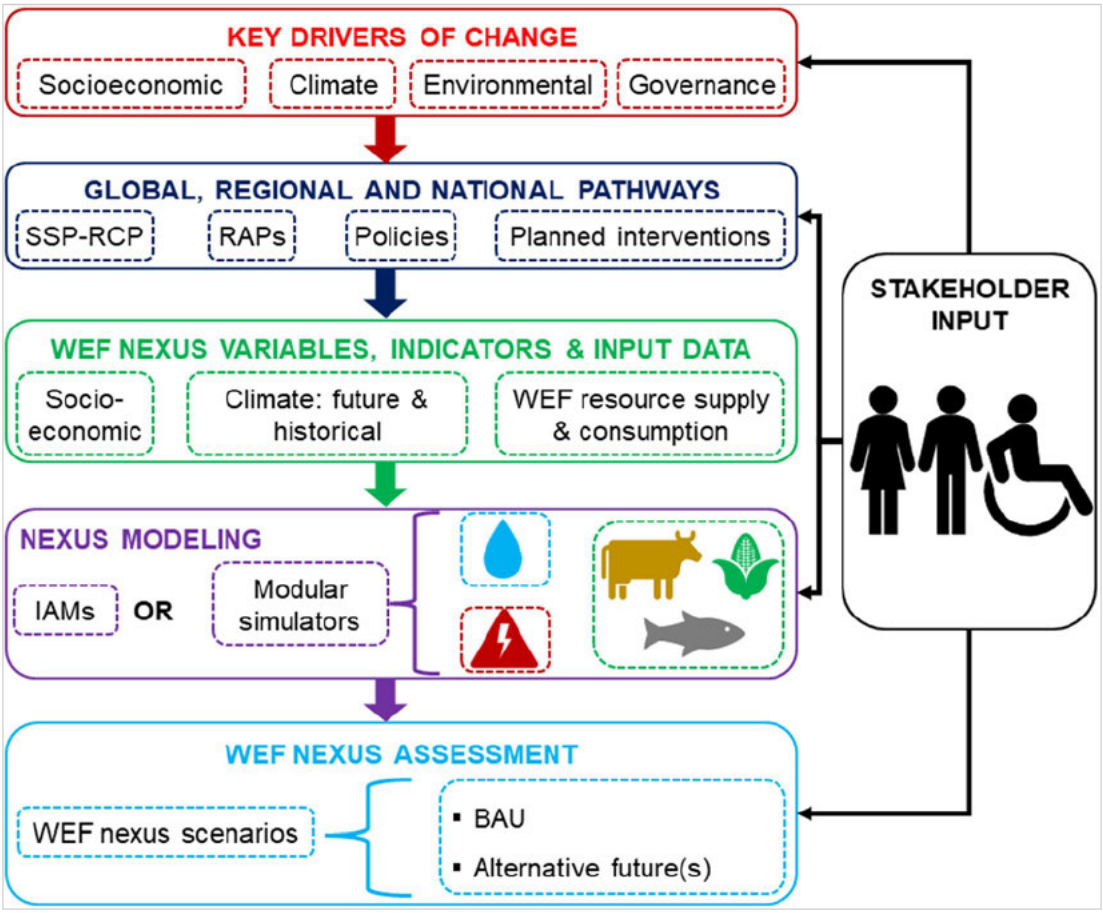


Figure 6.9: A generic people-centred and data-informed methodological framework for co-planning integrative WEF nexus scenarios (Abbreviations: SSP = Shared Socioeconomic Pathway; RCP = Representative Concentration Pathway; Representative Agricultural Pathway; WEF = water-energy-food; IAM = Integrated Assessment Models; BAU = business-as-usual)

These development activities were carried out iteratively with feedback from experts and the project team. Key features of the generic framework include stakeholder engagement, drivers of change, pathways, variables/indicators, input data, analytic tools and WEF nexus futures (scenarios). The framework is adaptable for water, energy, food and WEF nexus modelling tools, which can be selected and applied depending on the prevailing objective(s). Similarly, the nexus dimensions can be extended beyond WEF to include additional dimensions that may be relevant, such as the environment, land, ecosystem, biodiversity, health and economy. More details on the key features/elements of the 'generic people-centred and data-informed methodological framework for co-planning integrative WEF nexus scenarios' are provided in the descriptions of the key steps of the related generic iterative guidelines in preceding sections.

6.3.3.2 *Generic people-centred and data-informed methodological guidelines for co-developing integrated WEF nexus scenarios*

To bridge the aforementioned gaps in methodological guidelines with reproducible and repeatable procedures/activities for WEF nexus scenario planning, this section uses existing guidelines as foundation as well as some key elements of WEF nexus scenario planning from literature for enrichment, in the McMeekin *et al.* (2020) methodology, to develop generic people-centred and data-informed methodological guidelines for co-developing integrated WEF nexus scenarios (Figure 6.10).

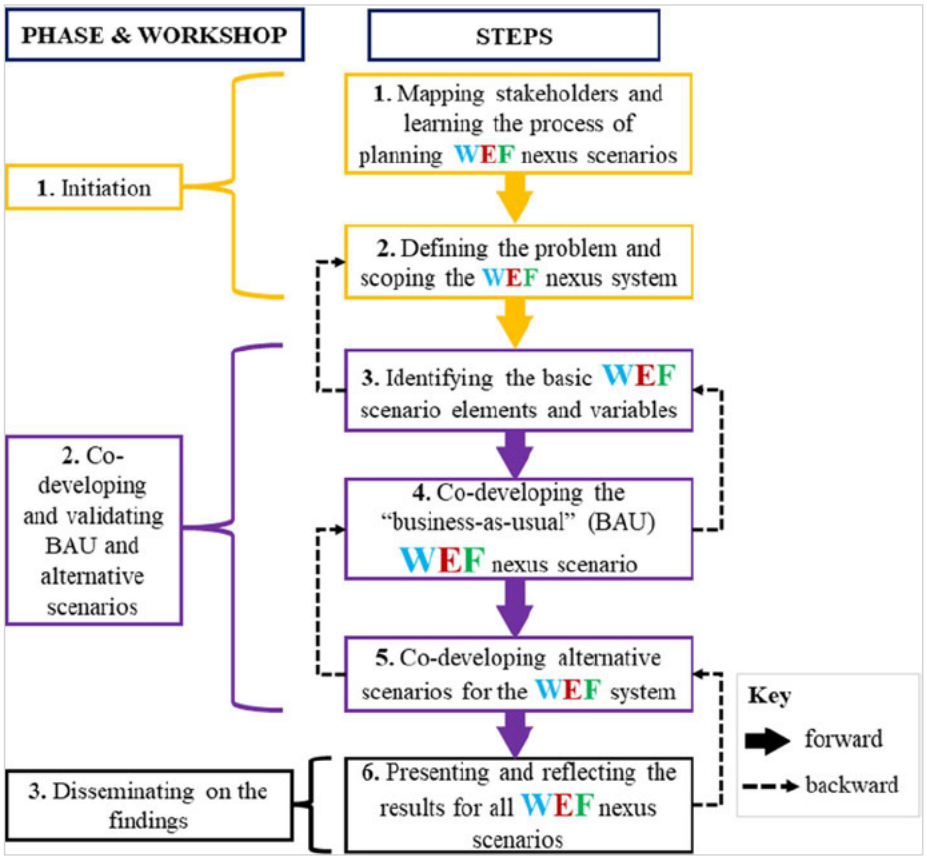


Figure 6.10: Iterative generic people-centred and data-informed methodological guidelines for co-developing integrated WEF nexus scenarios (Abbreviations: WEF = water-energy-food; BAU = business-as-usual)

These development activities were carried out iteratively with feedback from experts and the project team. The 'generic people-centred and data-informed methodological guidelines for co-developing integrated WEF nexus scenarios' chronologically the outlines key tasks and steps

for implementing the ‘generic people-centred and data-informed methodological framework for co-planning integrative WEF nexus scenarios’ (Figure 6.9), i.e., development and exploratory analytic modelling of integrative WEF nexus scenarios based on socioeconomic, climate change and agricultural evolution pathways. The proposed iterative generic guidelines for WEF nexus scenario planning consist of six steps in three phases ideally accomplished by three stakeholder (technical and non-technical) workshops, jointly seeking to present the current state of WEF nexus, and qualitatively and quantitatively explore scenarios about how the future might unfold (Johnson and Karlberg, 2017).

Step 1: Mapping stakeholders and learning the process of planning WEF nexus scenarios

The first step involves assembling the research/implementation team, identifying expert and non-expert stakeholders, considering the team's expertise across the relevant nexus disciplines, and establishing the power/influence of the stakeholders (Ghafoori-Kharanagh *et al.*, 2021). This initial list of stakeholders can be iteratively extended along the way when the need arises, for example through, among others, online investigation, and purposive, convenience and snowball sampling (Kotir *et al.*, 2016; Martinez *et al.*, 2018). Stakeholder’s interests and attitudes need to be identified and examined to search for possibilities of mutual benefits and identifying barriers to reaching consensus (Baba *et al.*, 2018). Deliberate efforts need to be taken to ensure equal recognition and representation of diverse individuals, including the marginalised and vulnerable stakeholders, to ensure gender equality and social inclusion, and leverage transdisciplinarity, and knowledge co-creation and integration (Jalonen *et al.*, 2022; Newman *et al.*, 2024). This step also entails introduction of project idea and training the stakeholders and other team members on concepts, processes, and methods such as nexus thinking, scenario planning, pathways, analytic tools, and documentation/reporting templates (Johnson and Karlberg, 2017; Martinez *et al.*, 2018; Gallagher *et al.*, 2020). Stakeholders can also contribute, critique and provide feedback on proposed methods and tools in this step, for example the assessment criteria and measures, and performance indicators of their interest (Johnson and Karlberg, 2017; Marttunen *et al.*, 2019).

Step 2: Defining the problem and scoping the WEF nexus system

In this second step, stakeholders are engaged, for example through interviews, workshops and questionnaires, to elicit local knowledge on the WEF-related problems and challenges (environmental, social, economic), possible intervention points, corresponding policy objectives and measures, and relevant overarching developments (e.g., adaptation and mitigation), as well as stakeholder priorities, assumptions, and perceptions (e.g., risks) (Johnson and Karlberg, 2017; González-Rosell *et al.*, 2020). Stakeholders can also provide relevant information on resource utilisation and allocation mechanisms, thresholds, constraints, practices and preferences, and the characteristics of livelihoods (Bakhshianlamouki *et al.*, 2020; Dhaubanjar *et al.*, 2021). Stakeholders are also engaged to identify on the main WEF nexus elements and interconnections (system and boundary definition), driving forces and uncertainties, the cause-and-effect relationships and their weights, mechanisms underlying trade-offs, and related socio-ecological impacts in the case study (Ghafoori-Kharanagh *et al.*, 2021; Sušnik *et al.*, 2021). The nexus system model representation should be conceptualised beyond WEF to account for livelihood dimensions including human health and environment/ecosystems (Gallagher *et al.*, 2020; Geressu *et al.*, 2020). The activities in this step potentially integrate local knowledge and expert knowledge as a foundation for developing potential initial future storylines, thus fulfilling a core objective of participatory planning of WEF nexus scenarios with the people whose futures are under discussion (Hoolohan *et al.*, 2019; Terrapon-Pfaff *et al.*, 2021).

Step 3: Identifying the basic scenario elements and variables

The third step identifies, defines and clarifies the basic elements of the scenarios and the variables of interest. These elements of analysis include spatial and temporal scales, global pathways and related assumptions (e.g., SSPs, RCPs and RAPs), intervention pathways, and the number of scenarios, including BAU and alternative futures. It is in this step that the temporal scale is articulated, that is, the time horizon(s) of analysis, including baseline and future(s) with a primary focus on local/national or international/global development timelines such as national/regional visions and Sustainable Development Goals (SDGs) (Johnson and Karlberg, 2017; Wada *et al.*, 2019). The analytic methods and tools and data sources are also

deliberated on in this step, depending on the scale and objective of analysis and potentially including agent-based modelling (ABM) (Abdel-Aal *et al.*, 2020), System Dynamics Modelling (SDM) (Bakhshianlamouki *et al.*, 2020; Sušnik *et al.*, 2021), and WEAP and LEAP (Johnson and Karlberg, 2017; Terrapon-Pfaff *et al.*, 2021). This step also involves identifying specific variables including targets, key parameters, assessment criteria, trends, thresholds, indicators, and indices to be considered, and a process for quantifying their changes over the time horizon of the analysis (Johnson and Karlberg, 2017; González-Rosell *et al.*, 2020). These variables may be based on performance metrics on resource security including availability, efficiency, productivity, reliability, resilience, and sustainability (Kotir *et al.*, 2016; Siderius *et al.*, 2021).

Step 4: Co-developing the "business-as-usual" (BAU) WEF nexus scenario

The team and stakeholders co-develop short initial narratives /storylines (qualitative scenarios) for an initial "business-as-usual" (BAU) scenario which assumes that all existing drivers of change (e.g., climate change, socioeconomic evolution) and resource management practices remain the same, or change according to historical trends (Johnson and Karlberg, 2017; Terrapon-Pfaff *et al.*, 2021). The variables for the "business-as-usual" (BAU) WEF nexus scenario are quantified, discussed and documented, including trends of drivers of change (Gallagher *et al.*, 2020; Sušnik *et al.*, 2021). Data sources may include literature (academic and grey), relevant policy, reports, repositories (local and global), databases, stakeholder input, and dedicated thematic models (Hoolohan *et al.*, 2019; González-Rosell *et al.*, 2020). On agreement of the inputs, the BAU scenario is modelled and analysed, and the analytic tools are calibrated. The research team reports findings of the BAU scenario to the stakeholders for discussion, checking consistency and iterative refinement until they reach a consensus (Gallagher *et al.*, 2020). Stakeholders have a role to play here, including validating inputs, assumptions and modelling results (Kotir *et al.*, 2016; Almulla *et al.*, 2020), and external researchers/experts may be invited for independent validation, verifying the logical validity and probability (Baba *et al.*, 2018).

Step 5: Co-developing alternative scenarios for the WEF system

The likely "pathway of change" of social-ecological WEF systems occurs discontinuously, instead of simply following a continuous pattern from the present to the future, and this requires thinking beyond the BAU scenario in pursuit of a well-informed decision for the future (Johnson and Karlberg, 2017; Baba *et al.*, 2018). Thus, this step requires the identification and development of narratives or qualitative scenarios or storylines and quantifying their variables for alternative WEF pathways based on deviations of trends from the BAU scenario (González-Rosell *et al.*, 2020; Ghafoori-Kharanagh *et al.*, 2021). The alternative pathways seek to explore plausible futures by considering potential interventions, development, actions, polices, decision options (e.g., planned reservoirs, irrigation sites), resource allocation mechanisms, likely changes in socioeconomic conditions, and climate change projections (Johnson and Karlberg, 2017; Kulat *et al.*, 2019). Alternative scenarios may include 'nexus' scenarios seeking to address WEF conflicts and trade-offs through use of individual or integrated 'nexus' innovations or solutions, or nexus-compliant strategies (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017; Martinez *et al.*, 2018). Individual or integrated (joined-up) 'nexus' innovations or solutions are technologies and practices, may be neither new nor mainstream, that potentially reduce negative impacts of WEF provisioning, and address overarching challenges such as climate change and inequality (Hoolohan *et al.*, 2019; Larkin *et al.*, 2020). Such innovations or solutions potentially benefit more than one sector and improve overall resource use efficiency, while reducing the pressure on ecosystems and the environment, improving resilience of socio-economic activities to external shocks (e.g., climate change), and strengthening policy coherence by minimizing negative externalities (UNECE, 2015; De Strasser *et al.*, 2016). According to IRENA and FAO (2021), integrated WEF systems fully account for the resource interconnections to optimise resource use and advance circularity thereby harnessing synergies and managing trade-offs. However, the suggested intervention and development pathways need to consider equitable redistribution of resources for addressing gender equality and social inclusion in the WEF nexus (Jalonen *et al.*, 2022; Jalonen *et al.*, 2023).

On agreement of the right and realistic mix of the pathways in scenarios, the alternative WEF nexus scenarios are subjected to exploratory modelling analysis (Borgomeo *et al.*, 2018). This involves exploring, modelling, simulating, optimizing, reflecting and analysing, from a nexus perspective, the multidimensional implications of the initial narratives or qualitative WEF

nexus scenarios and their sensitivity, and making recommendations for selecting and prioritising action plans, investment portfolios (including infrastructure development) and reforms for policy and governance (Johnson and Karlberg, 2017; Hoolohan *et al.*, 2019; Ghafoori-Kharanagh *et al.*, 2021). It is here wherein clear, yet unresolved, conflicts, risks and trade-offs over policies, measures, practices and interventions are revealed (Johnson and Karlberg, 2017). Similarly, this step is "a vehicle for pseudo-experimentation" as a non-threatening creative space for investigating possible pathways for action and intervention including technology, practices and policy (Hoolohan *et al.*, 2019).

6.3.3.2.1 Step 6: Disseminating the findings for all WEF nexus scenarios

In this step, team members present and elaborate all WEF nexus scenarios to the entire research/implementation team and all stakeholders for peer and stakeholder review for validation, substantiation and refinement (Gallagher *et al.*, 2020; González-Rosell *et al.*, 2020). The key message to be presented includes scenario results, research highlights, and recommendations while the audience should preferably include policymakers, and external researchers or invited experts for feedback and validation (Wada *et al.*, 2019). If feedback from stakeholders (and external researchers or invited experts) is negative, for example due to overlooked interrelationships, challenges or issues/priorities/questions and emerging data sources, the team may repeat steps 3-5 to revise the BAU and alternative future WEF nexus scenarios (Tan and Yap, 2019; González-Rosell *et al.*, 2020). Such new data and understanding can be obtained from subsequent steps, which could inform a better previous step (Tan and Yap, 2019). Similarly, the opinions and feedback can be considered and recorded for the refinement of scenarios and development of future studies (González-Rosell *et al.*, 2020). Complex information and decisions should be presented to non-technical stakeholders in an accessible and friendly way (Johnson and Karlberg, 2017). For example, the implications for policy and governance are discussed and use can be made of graphic visualisation aids such as radar charts (spider diagrams) and linear plots (Gallagher *et al.*, 2020; González-Rosell *et al.*, 2020). Use can also be made of tools that simplify understanding of the complexity such as parallel axis plots, directional nexus chord plots, Sankey diagrams and serious games (Knox *et al.*, 2018; van Vuuren *et al.*, 2019; Geressu *et al.*, 2020; Laspidou *et al.*, 2020; Sušnik *et al.*, 2021). If all stakeholders agree on the findings, they can use the quantitative evidence to enrich

the initial narrative scenarios and into policy briefs, development programs and action plans for implementation (Baba *et al.*, 2018).

6.3.3.3 Summarising the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios

Co-development of WEF nexus futures requires appropriate representation of the complex human-environment system and its associated management practices and policies through co-producing models and indicators (Momblanch *et al.*, 2019; Kliskey *et al.*, 2023). The deliberate involvement of relevant people, i.e., stakeholders, in WEF nexus scenario planning accrues multiple benefits to the process and outcomes, including the integration of expert knowledge and local knowledge (key questions, regional context, history, development challenges and priorities) to represent multiple perspectives (Momblanch *et al.*, 2019), promoting dialogue on multiple perspectives (Martinez *et al.*, 2018; Gerlak *et al.*, 2021), raising awareness and building consensus (Martinez *et al.*, 2018), participatory action and facilitating ownership (van Vuuren *et al.*, 2012), ensuring acceptability, legitimacy, credibility, reality, clarity, reliability, relevancy, and salience of scenarios (Valdivia *et al.*, 2015; UNDESA, 2016; Rosenzweig *et al.*, 2021), and building narratives of potential change (Rosenzweig *et al.*, 2016). Similarly, the participation of transdisciplinary stakeholders through reflection and exploration assists to unsettle established perspectives and practices, while creatively expanding the possibility space (Hoolohan *et al.*, 2019). However, the process has some inherent challenges.

Although they are presented here as distinct, linear steps, the six steps presented in the preceding sections are generic, dynamic and interactive and not prescriptive (Figure 6.10) (Karlberg *et al.*, 2015; Hoolohan *et al.*, 2019; González-Rosell *et al.*, 2020). The process is multi-faceted and iterative, requiring constant dialogue with the stakeholders, and sometimes it may be necessary to go back to previous steps, for example to refine and redefine elements, variables, storylines, narratives, qualitative scenarios, nexus interconnections, pathways and models (Johnson and Karlberg, 2017; Tan and Yap, 2019; Sušnik *et al.*, 2021). Similarly, some of the steps may be accomplished simultaneously, for example in one workshop, for instance Steps 2-3 and Steps 4-5. Thus, depending on the context (i.e., scale, objectives), availability of resources (e.g., time, financial, data), and cooperation of stakeholders, undertaking all the six steps of co-developing integrated WEF nexus scenarios may potentially take between one and

three years, or even more (Wada *et al.*, 2019; Siderius *et al.*, 2021; Sušnik *et al.*, 2021; Vinca *et al.*, 2021). While local civil society groups and local government participants can participate together in workshops for planning WEF nexus scenarios, the latter may be engaged separately from community representatives such as those for farming and fishing to avoid the negative influence of power dynamics arising from visible and invisible social, political, and cultural structures on information sharing and interpretation (Gallagher *et al.*, 2020). Depending on the context, some stakeholders may need extra efforts for them to respond positively to engagement and these include those from government agencies, utility companies, departments and ministries such as energy and agriculture (Johnson and Karlberg, 2017; Hoolohan *et al.*, 2019). Nevertheless, such participatory WEF nexus scenario planning processes congregate and trigger engagement between stakeholders who rarely cooperate and is thus a platform for breaking the sectoral silos, a key objective of the WEF nexus approach (Johnson and Karlberg, 2017; Hoolohan *et al.*, 2019).

6.3.3.4 Validation of the people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios

The generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios were developed and tested for rigour using the stepwise and iterative methodology proposed by McMeekin *et al.* (2020). The multistakeholder, multidisciplinary and transdisciplinary forums that were used for validation included special sessions during two WaterNet/WARFSA/GWP-SA symposiums, two cohorts of the WEF Nexus Winter School (now Advanced School), Reference Group Meetings for two Water Research Commission projects, sub-catchment management forum meetings in IUWMA, and engagement with key WEF-related expert stakeholders in Ehlanzeni DM (South Africa), Mzingwane Catchment and Umzingwane District (Zimbabwe). Throughout all these interactions with scientists and stakeholders, the main feedback included emphasis on stakeholder engagement, using the updated and recent pathways especially for climate change and socio-economic conditions, data availability, and applicability of the framework and guidelines at sub-national scales such as district and local municipality wherein WEF services and provisions are provided. Some of these issues were clarified during the presentations while some were used to improve on the structure and content of the generic people-centred and data-

informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. Further applied validation of the generic people-centred and data-informed methodological framework and guidelines is ongoing through co-developing integrated WEF nexus scenarios in South Africa (IUWMA and Ehlanzeni DM) and Zimbabwe (Mzingwane Catchment and Umzingwane District).

6.4 Conclusions and Recommendations

Although several authors claim that WEF nexus studies have tended to focus on historical and current periods (Hoolohan *et al.*, 2018; Hoolohan *et al.*, 2019; Molajou *et al.*, 2021; Newman *et al.*, 2024), this study found that scenario planning has been applied in WEF nexus studies across multiple temporal and spatial scales, considering major drivers of change, and using an array of integrated analytic frameworks and models. However, a minority of these studies explicitly reported engagement of stakeholders, and reproducible methodological frameworks and guidelines which may limit broader use and uptake. Based on published literature on WEF nexus scenario planning, this study developed generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios, building on how scenario planning was previously applied in WEF nexus studies. Preliminary findings from validation through interaction and with feedback from experts and stakeholders shows that the developed generic people-centred and data-informed methodological framework and guidelines can be further tested, validated and refined through application in co-developing integrated WEF nexus scenarios with stakeholders, especially in case studies such as those in progress in South Africa (Inkomati-Usuthu Water Management Area, IUWMA; Ehlanzeni District Municipality, EDM) and Zimbabwe (Mzingwane Catchment MC; Umzingwane District, UD).

WEF nexus scenario planning studies should engage stakeholders to enhance, among others, cross-fertilisation of knowledge, and consideration and representation of the local context. Similarly, frameworks and guidelines for WEF nexus scenario planning need to prioritise and be centred on the people. While using these or any other methodological framework and guidelines, research, inquiry and practice in WEF nexus scenario planning need to stay up to date by applying latest and updated pathways, such as the CMIP6 SSPX-Y for likely evolution in climate and socio-economic conditions. Similarly, researchers, practitioners, and planners are encouraged to use the RAPs, which are compatible with SSPs and RCPs, to systematically

envision and explore the likely evolution of agricultural systems. In the same vein, the water and energy communities are encouraged to develop replicable and reliable methodologies for developing regional and local pathways for water and energy systems as inherently linked to the latest SSPs and RCPs. The deliberation of the key elements of WEF nexus scenario planning, for example important pathways and drivers, need to be co-decided with those affected by and affecting the current and future nexus in discussions and analysis. All these efforts are necessary for seamless development and exploration of aligned, relevant, consistent and coherent integrated WEF nexus scenarios that can inform long term integrative planning and development of WEF transitions that are robust, resilient and sustainable in the face of likely change.

Future research needs to collate and synthesise the multidimensional implications of different drivers of change and pathways (e.g., interventions, developments and strategies) on the future WEF nexus scenarios. Similarly, such analysis must highlight the synergies and trade-offs (maladaptation) from adaptive actions. Such studies need to be done for regions demarcated on common WEF challenges as a starting point to inform and guide researchers, practitioners, decision-makers and policy-makers in identifying bespoke regionally differentiated and contextually specific WEF investment portfolios.

6.5 References

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7 CONCLUSIONS AND RECOMMENDATIONS

Despite the gain in momentum in all three dimensions of the WEF nexus approach in research and policy, its implementation is hindered by the lack of bespoke analytic tools and insufficient empirical evidence. This study sought to bridge these gaps by developing an open access GIS-enabled multiscalar WEF nexus analytic tool, applying it with stakeholders in sub-national case studies to generate baseline evidence, and developing generic people-centred and data-informed methodological framework and guidelines for co-developing WEF nexus scenarios. It is envisaged that these tools and empirical evidence will support and facilitate the much-awaited implementation of the WEF nexus approach in southern Africa and other areas of almost similar context in the global South.

7.1 Summary

To develop bespoke tools and empirical evidence for supporting and facilitating implementation of the WEF nexus approach, this study employed multiple methods including systematic review of literature, computer-based model building, stakeholder engagement, analytic modelling, and methodological framework and guidelines development.

7.1.1 Status of water-energy-food (WEF) nexus tools in theory and practice

In Chapter 2, the study assessed evidence and characteristics of WEF nexus tools in theory and practice by systematically reviewing literature on WEF nexus tools using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol.

7.1.2 A geospatial web-based integrative analytical tool for the water-energy-food (WEF) nexus: the iWEF 1.0

In Chapter 3, model building, programming, web development, and GIS integration tools were used to develop a geospatial web-based integrative analytical tool for the WEF nexus (the

iWEF). The iWEF tool uses the Analytic Hierarchy Process (AHP) to establish numerical correlations among WEF nexus indicators and pillars, mainly availability, productivity, accessibility, and sufficiency. The tool was calibrated and validated with existing tools and data at varying spatio-temporal scales.

7.1.3 The state of the water-energy-food nexus at sub-national scales (catchment and district): cases of South Africa

In Chapter 4, mixed methods including the iWEF tool were used to assess the state of the WEF nexus at sub-national scales in IUWMA and Ehlanzeni DM in South Africa. The qualitative research methods constituted interviews and discussion guides administered to key expert stakeholders in the WEF-related sectors during catchment management forums in the case study areas, whose input data was analysed in the iWEF tool. The quantitative research methods included conjunctive use of the iWEF tool and established databases, reports and literature for reviewing secondary data and collecting information related to WEF resources supply, demand, utilization, management, and prioritised, planned and ongoing interventions and developments. This data and ground observations were used to interpret the results from the iWEF model and providing nexus-relevant recommendations.

7.1.4 The state of the water-energy-food nexus at sub-national scales (catchment and district): cases of Zimbabwe

In Chapter 5, mixed methods including the iWEF tool were used to assess the state of the WEF nexus at sub-national scales in MC and UD in Zimbabwe. The qualitative research methods constituted interviews and discussion guides administered to key expert stakeholders one-on-one in the WEF-related sectors in the case study areas, whose input data was analysed in the iWEF tool. The quantitative research methods included conjunctive use of the iWEF tool and established databases, reports and literature for reviewing secondary data and collecting information related to WEF resources supply, demand, utilization, management, and prioritised, planned and ongoing interventions and developments. This data and ground

observations were used to interpret the results from the iWEF model and providing nexus-relevant recommendations.

7.1.5 A people-centred and data-informed framework and guidelines for developing integrated water–energy–food nexus scenarios

Chapter 6 used mixed approaches to develop a people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios. This was achieved in three chronological steps: (i) systematic literature review for searching foundations and building blocks (key elements of WEF nexus scenario planning, steps, procedures, existing frameworks and guidelines), (ii) using the evidence from the first step and feedback from experts to draft and iterate the people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios, and (iii) evaluating and refining the developed generic people-centred and data-informed methodological framework and guidelines through discussions and interactions with expert and non-expert stakeholders. Further applied testing and validation are ongoing through application in two districts and two catchments in South Africa (IUWMA, Ehlanzeni DM) and Zimbabwe (MC, UD).

7.2 Originality

The original outputs of this study include:

1. A geospatial web-based integrative analytical tool for the water-energy-food nexus (iWEF, https://www.iwef.app/).
2. Baseline empirical evidence to support implementation of the WEF nexus approach at sub-national scales (catchment, district) in South Africa and Zimbabwe, relatable to other areas of similar context in southern Africa.
3. Generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

7.3 Conclusions

The questions and objectives of this research were addressed and achieved, respectively, and the following conclusions were drawn.

7.3.1 Status of WEF nexus tools in theory and practice

The broader accessibility, uptake, and utility of a majority (61%) of WEF nexus tools is limited by their general unavailability and limited functions, which undermines their robustness, rigour and uptake in implementation of the WEF nexus approach. Other limitations of existing WEF nexus tools are related to (i) the need for specialised skills (e.g., programming, analytic), (ii) location and scale specificity, and (iii) and lack of geospatial capabilities.

7.3.2 A geospatial web-based integrative analytical tool for the water-energy-food (WEF) nexus: the iWEF 1.0

The iWEF is a multiscalar, user-friendly and open access tool that accurately determines the consistency of stakeholder input, and computes the normalised indices and integrated WEF nexus composite indices which can be retrieved and visualised quantitatively and spatially. To conclude, the iWEF tool is a digital platform that can be used to support integrated assessment of WEF resources management for guiding policy and decision-making on timely harmonised interventions, adaptation initiatives and strategies that manage risk from trade-offs and enhance synergies holistically towards resilience and sustainability in priority areas.

7.3.3 The state of the water-energy-food nexus at sub-national scales (catchment and district): case of South Africa

The state of WEF nexus is moderately sustainable in IUWMA and Ehlanzeni DM due to unbalanced management of WEF resources, as evidenced by frequent water outages/rationing, incidence of waterborne diseases (e.g., cholera), frequent electricity load shedding, hunger and

malnutrition, coal mining-land-water-environment trade-offs, and the stagnating and slow progress in achieving SDGs. The iWEF tool is useful and reliable for breaking silos by bringing together WEF stakeholders to co-analyse the WEF nexus across multiple scales, and co-plan and harmonise activities, policies and interventions among the WEF sectors in southern Africa and beyond.

7.3.4 The status of the water-energy-food nexus at sub-national scales (catchment and district): case of Zimbabwe

The state of WEF nexus, and security and management of WEF resources in MC and UD is moderately sustainable and unbalanced, as evidenced by frequent water rationing, incidence of waterborne diseases (e.g., cholera), long episodes of electricity load shedding, widespread hunger and malnutrition, gold mining-land-water-environment trade-offs, and the slow (and some deteriorating) progress in achieving SDGs. The iWEF tool can be used at sub-national scales (e.g., hydrologic, administrative) in southern Africa and similar regions for facilitating implementation of the WEF nexus approach through, among others, congregating WEF stakeholders, to co-analysing the WEF nexus, and co-planning and harmonising activities, policies and interventions among the WEF sectors.

7.3.5 A people-centred framework and guidelines for developing integrated water–energy–food nexus scenarios

Scenario planning has been applied in WEF nexus studies across multiple temporal and spatial scales, considering major drivers of change, and using an array of integrated analytic frameworks and models, while a minority mentioned the involvement of stakeholders and provided methodological frameworks and guidelines. To conclude, validation by stakeholders and experts triggered refinement and enhanced the robustness and rigour of the generic people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios.

7.4 Key Recommendations

The study sought to further develop and improve the MS Excel based integrative analytical model for the WEF nexus (Nhamo *et al.*, 2020) and apply it in case studies, and develop a people-centred framework and guidelines for developing integrated water–energy–food nexus scenarios. The following recommendations can be drawn from the study:

1. The WEF nexus community is encouraged to promote the availability and open access of WEF nexus analytic tools, and further improving, on-demand, the capabilities of WEF nexus tools.
2. The WEF nexus community of researchers and practitioners is encouraged to use the iWEF tool with stakeholders in implementing the WEF nexus approach across multiple scales.
3. Implementation of the WEF nexus approach across multiple scales in southern Africa and beyond requires assessing, ex ante, the multidimensional economy-wide and cross-sectoral implications of policies, planned or ongoing efforts (e.g., irrigation development, just energy transition, decommissioning of coal-fired power stations and commercial production of hydrogen) to improve WEF resource security. This can potentially benefit from using the iWEF tool and WEF nexus scenario planning frameworks and guidelines, and the gained evidence would facilitate harmonisation of WEF-related policies and activities.
4. Case studies with stakeholder engagement and updated pathways are required to further test, validate and refine the people-centred and data-informed methodological framework and guidelines for co-developing integrated WEF nexus scenarios at multiple scales.

8 APPENDICES

8.1 Appendix A: Brief Summaries of Existing WEF Nexus Tools

WEF Nexus Tool	**Short Description**
WEF Nexus Discovery Map (1)	WEF Nexus Discovery Map is a map-based pool/database of catalogued and classified WEF nexus information from otherwise geographically and topically diverse independent and academic communities worldwide. It shows WEF nexus projects' specific information, such as the institution that produced the work, local collaborators, relevant web page, and point of contact. The WEF Nexus Discovery Map dashboard incorporates the WEF Nexus Index Map (Arenas *et al.*, 2021).
BP-DEMATEL-GTCW (2)	Back Propagation neural networks–DEcision Making Trial and Evaluation Laboratory–Game Theory Combination Weight (BP-DEMATEL-GTCW) Model is a two-step measurement model for the symbiotic and symbiotic level indices used to study the nexus in the form of the WEF ecosystem from the perspective of WEF symbiosis. Its applications include identifying key influencing factors that affect the symbiotic security of the WEF ecosystem (Chen and Chen, 2021).
ITEEM (3)	Integrated Technology-Environment-Economics Model (ITEEM) integrates various models for technology (grain processing, drinking water treatment, environment (watershed model for hydrology, water quality, crop production, nutrient cycling), and an economics model for assessing total benefit that includes non-market evaluation of environmental benefits (Li *et al.*, 2021).
WEF-Sask (4)	Water-Energy-Food (WEF) - Sask (WEF-Sask) Model integrates production (supply) and demand sides of WEF systems into a single system-of-systems model using the system dynamics approach to gain insights into inevitable trade-offs and synergistic interactions between WEF systems under challenges brought by socioeconomic and climatic changes and limited water resources (Wu *et al.*, 2021).
CALFEWS (5)	California Food-Energy-Water System (CALFEWS) links the operation of state-wide, inter-basin transfer projects with coordinated water management strategies abstracted to the scale of irrigation/water districts to describe the integrated, multi-sector dynamics that emerge from the coordinated management of surface and groundwater supplies (Zeff *et al.*, 2021).
NeFEW (6)	Nexus of Food, Energy, and Water (NeFEW) Toolbox is a data analysis toolbox for synthesizing available global data to enable estimating country-specific estimates of water resources (blue, green, grey) required to produce different types of food and energy, the energy required per quantity of water or agricultural product supplied, and CO2-equivalent emissions associated with water and energy provision (Sadegh *et al.*, 2020).

MAXUS Model (7)	MAXUS highlights, simulates, and optimizes inter-sectoral and international development strategies in the WEF sectors. The model consists of an objective function, balances, dimensions, constraints and decision variables (Burger and Abraham, 2020).
WEF Nexus SD (8)	The Water-Energy-Food Nexus System Dynamics (WEF Nexus SD) Model is based on system dynamics to study intricate connections between WEF and specific supply-and-demand mechanisms of water resources in each sub-system. The sub-systems include the external social, economic, and eco-environmental, all integrated by the model to determine the dynamic balance of water resources (Chen and Chen, 2020).
FPC (9)	Farm Performance Calculator (FPC) contains data and conversion coefficients derived from the (FArming Tools for external nutrient Inputs and water MAnagement) FATIMA project to calculate indicators and conduct energy, economic and environmental analysis for a simplified evaluation and analysis of the WEF nexus at the farm level. The main input for the calculator consists of agricultural and energy, while the main output consists of computations for the energy, water and food indicators (Fabiani *et al.*, 2020).
WEF-P (10)	Water-Energy-Food Nexus Phosphate (WEF-P) Tool is an adaptation of the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015). WEF-P assesses the impact of various scenarios and possible responses to resource management needs, by considering the supply the supply chain of the final product in terms of its resource consumption, including the set of processes that pass materials forward and various organizations/individuals directly involved in the flow of the products (Lee *et al.*, 2020).
SD-WFE (11)	System Dynamics Water–Food–Energy (SD-WFE) Model is a spatiotemporal disaggregated WEF nexus model that assesses water and food supply security considering ecosystem provisioning services. The model contains modules for population, water, agriculture, and energy (Ravar *et al.*, 2020).
WEST (12)	WEST (Water Economy Simulation Tool) is a simulation model that incorporates water, energy, food, and detailed economic data, usable for standalone analysis or incorporated, to show how jobs and economic growth interact with surface and groundwater use, food and energy (Reimer *et al.*, 2020).
MIFCP-WEFN (13)	Multi-level Interval Fuzzy Credibility-constrained programming Water-Energy-Food Nexus (MIFCP-WEFN) Model helps plan the regional-scale WEF nexus system by identifying the optimal agricultural water resources management schemes through the leadership of water resources managers and the feedback of two diverse followers (i.e., managers for energy and agriculture) (Yu *et al.*, 2020).
NEST (14)	NExus Solutions Tool (NEST) is an open modelling platform for integrated energy-water-land EWL systems analysis under global change by a hard-linked integration of multi-scale energy-water-land resource optimization framework with distributed hydrological modelling. It integrates a distributed hydrological model and a resource supply planning model (Vinca *et al.*, 2020).

iWEF (15)	Integrative analytical model for the Water-Energy-Food nexus (iWEF) is an Analytic Hierarchy Process (AHP)-based model that establishes quantitative relationships among WEF nexus sectors, as well as an integrated nexus index that indicates resource utilization and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention (Nhamo *et al.*, 2020).
WEF Nexus Index (16)	The Water-Energy-Food (WEF) Nexus Index is a web-based WEF nexus global visualization map comprising an index that is a composite indicator derived from integrating WEF resource sectors' indicators. Within each resource are equally weighted 'access' and 'availability' sub-pillars, as well as relevant indicators from a total of 21 (Simpson *et al.*, 2020).
AWEFSM (17)	Agricultural Water-Energy-Food Sustainable Management (AWEFSM) Model integrates multi-objective programming, nonlinear programming, and intuitionistic fuzzy numbers into a general framework for the sustainable management of the limited water-energy-food resource in an agricultural system (Li *et al.*, 2019).
GREAT for FEW (18)	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus (GREAT for FEW) is based on the life cycle assessment (LCA) method for evaluating the FEW inter-linkages and informing decision-makers of the co-benefits and trade-offs from a wide variety of investments and policies for the present and the future. It combines a nexus assessment framework and a web-based GIS-enabled nexus platform that consists of a conceptual model, a database, and calculation methods (Lin *et al.*, 2019).
EPAT (19)	Energy Portfolio Assessment Tool (EPAT) is a scenario-based holistic nexus tool and platform for energy stakeholders and policymakers to create and evaluate the sustainability of various WEF nexus scenarios (Mroue *et al.*, 2019).
WHAT-IF (20)	Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF) is an open-source hydro-economic optimization model incorporating representations of the water, agriculture, and power systems in a holistic framework to explore joint development of nexus-related infrastructure and policies and evaluate their economic impact, as well as the risks linked to uncertainties in future climate and socio-economic development (Payet-Burin *et al.*, 2019).
K-WEFS (21)	Karawang Water-Energy-Food (WEF) Security (K-WEFS) Model is a system dynamic model that assesses the WEF nexus based on four scenarios: changes in population growth, agricultural land conversion rate, per-capita resource consumption, and the development of artificial ponds and solar energy (Purwanto *et al.*, 2019).
WEFSiM (22)	Water-Energy-Food (WEF) nexus Simulation Model (WEFSiM) is a system dynamics algorithm-based computer simulation and optimization model that calculates the supply and consumption, availability, and reliability of water, energy, and food resources nationwide considering the interconnections of resources (Wicaksono and Kang, 2019).

Daily (23)	Daily Model applies cost-benefit analysis to assess WEF nexus scenarios from integrating RiverWare, HEC-HMS, and CropWat that simulate hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply (Basheer *et al.*, 2018).
DAFNE (24)	The Decision-Analytic Framework to explore the water-energy-food NExus in complex and transboundary water resources systems of fast-growing developing countries (DAFNE) approach facilitates the quantitative assessment of the social, economic, and environmental impacts of expanding energy and food production in complex physical and political contexts, in interconnected natural and social processes, where the institutional setting involves multiple stakeholders and decision-makers. The approach consists of a Decision-Analytic Framework (DAF) for Participatory and Integrated Planning (PIP), an integrated WEF modelling framework and a web-based Negotiation Simulation Lab (NSL) (ETHZÜRICH, 2018).
SIM4NEXUS Models and Serious Game (25)	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe (SIM4NEXUS) Models and Serious Game consist of a WEF system dynamic integrated model and serious games for investigating potential plausible cross-nexus implications and synergies under different climate change and socioeconomic pathway scenarios due to policy interventions for 12 multi-scale case studies ranging from regional to global (Sušnik *et al.*, 2018).
UCEC (26)	Urban Circular Economy Calculator (UCEC) is an online open-access tool for cities to develop different circular economy scenarios associated with WEF management. Based on emergy accounting urban dynamic modelling, it uses WEF inputs from urban managers and policymakers to display the analysis of different urban circular economy scenarios considering technological roadmap alternatives performances from policy and technology solutions (Xue *et al.*, 2018).
ABM-SWAT Model (27)	Agent-Based Model - Soil and Water Assessment Tool (ABM-SWAT) is an integration of ABM and SWAT that assesses the impact of climate and human/anthropogenic changes on the water, energy, food, and ecosystem sectors and characterizes the resulting trade-offs through a set of generic metrics related to the sustainability of water availability (Khan *et al.*, 2017).
Nexus Game (28)	Water–Food–Energy Nexus Game is an integrated 'hardware' simulation game addressing the interrelated challenges of WEF production to meet demand. It is set on two riparian countries sharing a transboundary river basin, representing inter-ministerial and international negotiations wherein players encounter and learn potential technological solutions and relational challenges to reduce their WEF footprints (CSS *et al.*, 2017).
WEF Model (29)	Water-Energy-Food (WEF) Model is a system dynamics-based model that captures the interactions between WEF at household scale and end-use level by estimating WEF demand and the generated organic waste and wastewater quantities and investigating the impact of change in user behavior, diet, income, family size and climate (Hussien *et al.*, 2017).

Q-Nexus (30)	The Q-Nexus model is a quantitative WEF nexus assessment, simulation and optimization framework and platform to quantify, plan, simulate and optimize water, energy, and food as an interlinked system of resources that directly and indirectly affect one another. The model enables the analysis of WEF planning scenarios and policy options based on dynamic demand, technology and resource allocation (Karnib, 2017).
NexSym (31)	Nexus Simulation System (NexSym) is a modular tool based on a simulation and analytics framework for explicit systems dynamic modelling of local techno-ecological interactions relevant to WEF operations. It integrates models for ecosystems, technology, WEF production and consumption components, including waste treatment (Martinez-Hernandez *et al.*, 2017).
WEFO Model (32)	Water, Energy and Food security nexus Optimization (WEFO) is an integrated multi-period socioeconomic model analysis framework and tool for predicting how to satisfy WEF demands based on model inputs representing production costs, socioeconomic demands, and environmental controls. WEFO's management objective is to minimize the total system cost, a sum of energy supply, water supply, electricity generation, food production, and CO_2 emission mitigation costs (Zhang and Vesselinov, 2017).
SEWEM (33)	System-wide Economic-Water-Energy Model (SEWEM) is an advanced hydro-economic optimization model analyzing basin-wide energy production alternatives and energy demand restrictions for agricultural and industrial production and water supply systems (Bekchanov and Lamers, 2016).
BRAHEMO (34)	BRAhmaputra HydroEconomic MOdel (BRAHEMO) integrates physically-based spatially distributed hydrologic modelling, hydro-economic modelling, and ex-post scenario analysis to elicit the conditions of conflict and alignment of development trajectories (Yang *et al.*, 2016b).
IBMR-MY (35)	Indus Basin Model Revised-Multi Year (IBMR-MY) is a hydro-agro-economic model extended with an agricultural energy use module. Its objective function maximizes the net economic benefit (from crop production and hydropower generation) of water uses in the basin (Yang *et al.*, 2016a).
Pardee RAND WEF Security Index (36)	Pardee RAND Water-Energy-Food (WEF) Security Index is an online interactive WEF nexus security index with an unweighted geometric mean of three sub-indices, each for the three WEF sectors. Each sub-index comprises two or more indicators reflecting resource availability and accessibility (Willis *et al.*, 2016).
WEF Nexus Tool 2.0 (37)	The Water-Energy-Food (WEF) Nexus Tool 2.0 is a scenario-based tool that consists of inputs that reflect national food, water, and energy strategic options and allows for creating and assessing different scenarios to achieve sustainable resource management strategies for national food production. The tool uses an input-output modelling framework and food as an entry point for calculating nexus resource flows and interactions and greenhouse gas (GHG) emissions for a given food self-sufficiency level (Daher and Mohtar, 2015).

PRIMA (38)	Platform for Regional Integrated Modeling and Analysis (PRIMA) is an innovative modelling system to simulate interactions among natural and human systems at scales relevant to regional decision-making. PRIMA aims to enhance scientific understanding and facilitate effective decision-making related to regional interactions among climate, energy, hydrology, land use, and socioeconomics. PRIMA's modelling framework integrates various models of regional climate, hydrology, agriculture and land use, socioeconomics, and energy systems using a flexible coupling approach. Due to its modular framework and structure, PRIMA is customizable, portable and flexible (Kraucunas *et al.*, 2015).
EWF Nexus Tool (39)	Energy-Water-Food (EWF) Nexus Tool integrates energy, water, and food life cycle assessment in one robust holistic systems model of sub-systems at an appropriate resolution. The EWF Nexus Tool uses life cycle assessment principles to translate system outputs into environmental assessment scores, by operating through the four stages of life cycle assessment: the goal and scope definition, the life cycle inventory analysis; the impact assessment; and the interpretation of the results (Al-Ansari *et al.*, 2014).
WEF Nexus Assessment 1.0 (40)	Water-Energy-Food (WEF) Nexus Rapid Appraisal (or Nexus Assessment 1.0) Tool rapidly informs nexus-related responses regarding strategies, policy measures, planning and institutional set-up, or interventions regarding bio-economic pressures. It provides users with ten nexus context analysis indicators and 30 nexus intervention analysis indicators. The set of intervention scenarios includes power irrigation, bioenergy, hydropower and water desalination interventions from the perspective of water, energy, food, labor, and cost components (Flammini *et al.*, 2014).
Nexus Webs (41)	Nexus Webs is a conceptual–analytical model of the components and linkages in a river basin representing how water use changes impact livelihoods and wellbeing. The four linked components include water use, assets, ecosystem services and wellbeing (Overton *et al.*, 2013).
CLEWs (42)	Climate-, Land-, Energy- and Water-systems (CLEWs) tool applies a module-based approach to quantitatively and simultaneously assess/explore land, energy and water resource systems as closely linked resources (and climate) within a modelling framework that integrates detailed models from different tools. The tool iteratively passes data between sectoral models (Howells *et al.*, 2013).
WEAP – LEAP (43)	Water Evaluation And Planning System – Long-range Energy Alternatives Planning System (WEAP - LEAP) were integrated to become WEAP-LEAP for integrated research planning, analyses and decision-making of the closely interlinked energy and water systems. They are connected seamlessly by a common 'wizard' that allows exchanging parameters and outputs, such as hydropower generated or cooling water requirements, water supply characteristics for projecting energy demand, hydropower modelling and consistent weekly time-step calculations (SEI, 2012).
Foreseer (44)	The Foreseer Tool is a modular model for tracing and visualizing, using Sankey diagrams, the influence of future demand scenarios on requirements for energy, water, and land resources. The tool is based on a set of linked physical models for energy, water and land, or any other customized analyses such as climate change, technological change, or other effects (Allwood *et al.*, 2012).

ANEMI (45)	ANEMI is an integrated assessment model of global change that emphasizes the role of water resources. The model uses feedback processes among its sub-systems and system dynamics simulation principles to analyze changes in the Earth system. ANEMI3 assesses and describes the state of and interactions between the Earth system's model sub-systems (or sectors), mainly climate system, carbon, nutrient and hydrologic cycles, population dynamics, land use, food production, sea-level rise, energy production, energy, economy, persistent pollution, water demand and water supply development (Davies and Simonovic, 2010).
MuSIASEM (46)	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an integrated diagnostic and simulation tool that characterizes the metabolic pattern/flows of energy, food and water and their interlinkages about socio-economic (e.g., population dynamics) and ecological variables (e.g., land-use changes, greenhouse gas emissions) simultaneously. The MAGIC Nexus Game is a serious game based on MuSIASEM, to expose players to the main trade-offs and co-benefits in the nexus using a quantitative framework of relations between the nexus elements based on environmental footprint indicators (Giampietro *et al.*, 2009).

8.2 Appendix B: Characteristics of Existing 46 WEF Nexus Tools

Tool	**Availability**		**Format/form of tool**							**Spatial scale of application**					**Geospatial capabilities**	**Number of case studies**		
	Av	*W*	*DL*	*WA*	*DA*	*Cod*	*Ex*	*Ge*	*Un*	*G*	*Con, ER, B, Tr*	*Cou, N*	*P, SB, Ca*	*L (Sc, M, H, Ci, To, Proj)*		*L (1-3)*	*M (4-10)*	*H (>10)*
WEF Nexus Discovery Map (1)	✔	✔		✔						✔	✔	✔	✔	✔	✔			✔
BP-DEMATEL-GTCW (2)									✔		✔		✔	✔				✔
ITEEM (3)						✔					✔				✔	✔		
WEF-Sask (4)									✔		✔					✔		
CALFEWS (5)	✔	✔				✔						✔				✔		
NeFEW (6)	✔	✔			✔							✔				✔		✔
MAXUS (7)					✔							✔	✔	✔	✔			✔

WEF Nexus SD (8)						✔			✔			✔			
FPC (9)					✔					✔		✔			
WEF-P (10)						✔	✔					✔			
SD-WFE Model (11)						✔			✔						✔
WEST Tool (12)	✔	✔			✔			✔	✔			✔			
MIFCP-WEFN Model (13)						✔			✔			✔			
NEST Tool (14)	✔	✔			✔		✔				✔	✔			
iWEF Tool (15)					✔		✔	✔	✔	✔		✔			
WEF Nexus Index (16)	✔	✔	✔					✔			✔				✔
AWEFSM Model (17)						✔	✔		✔	✔		✔			
GREAT for FEW Tool (18)	✔	✔	✔					✔			✔	✔			
EPAT (19)						✔		✔	✔			✔			
WHAT-IF (20)	✔	✔			✔		✔		✔			✔			
K-WEFS (21)						✔				✔		✔			
WEFSiM (22)						✔		✔				✔			
Daily (23)						✔	✔		✔		✔	✔			
DAFNE (24)			✔			✔	✔				✔	✔			
SIM4NEXUS Model and Serious Game (25)	✔	✔				✔			✔		✔				✔
UCEC (26)	✔	✔	✔							✔		✔			
ABM-SWAT (27)						✔	✔					✔			
Nexus Game (28)	✔					✔	✔								✔
WEF (29)				✔						✔		✔			
Q-Nexus (30)	✔	✔	✔					✔					✔		

NexSym (31)				✔							✔		✔			
WEFO (32)							✔		✔				✔			
SEWEM (33)							✔		✔		✔		✔			
BRAHEMO (34)							✔		✔				✔			
IBMR-MY (35)							✔		✔				✔			
Pardee RAND WEF Security Index (36)	✔		✔		✔					✔						✔
WEF Nexus Tool 2.0 (37)	✔		✔		✔					✔					✔	
PRIMA (38)			✔	✔		✔					✔			✔	✔	
EWF Nexus Tool (39)							✔			✔					✔	
WEF Nexus Assessment 1.0 (40)			✔	✔			✔			✔	✔	✔			✔	
Nexus Webs (41)							✔	✔	✔	✔	✔	✔		✔		
CLEWs (42)	✔		✔		✔			✔	✔	✔	✔	✔	✔			✔
WEAP – LEAP (43)	✔		✔		✔			✔	✔	✔	✔	✔	✔			✔
Foreseer (44)			✔	✔		✔		✔	✔	✔			✔			✔
ANEMI (45)	✔		✔			✔		✔	✔	✔						✔
MuSIASEM (46)	✔		✔				✔			✔			✔			✔

Key: Av = availability; W = web availability; DL = dead (broken) link; WA = web application; DA = desktop applications; Cod = code; Ex = Excel worksheet; Ge = game; Un = unknown; G = global; Con, ER, B, Tr = Continental, Economic Region, Basin, Transboundary; Cou, N = Country, National; P, SB, Ca = Province, Sub-basin, Catchment; L (Sc, M, H, Ci, To, Proj) = Local (Sub-catchment, Municipal, City, Town, Household, Project); Ge = Geospatial capabilities / features; L (1-3) = Low case studies; M (4-10) = Medium case studies; H (>10) = High case studies

8.3 Appendix C: Saaty's Analytic Hierarchy Process (AHP) Scale of Relative Performance for Pairwise Comparisons

Intensity of performance	Definition
1	Equal performance
2	Weak performance
3	Moderate performance of one over another
4	Moderate plus performance
5	Essential or strong performance
6	Strong plus performance
7	Very strong or demonstrated performance
8	Very, very strong performance
9	Extreme or absolute performance
Reciprocals (inverse) of above nonzero values	Apply for the opposite of above-mentioned relationships

8.4 Appendix D: Computations in the Geospatial Web-based Integrative Analytical Tool for the Water-Energy-Food Nexus (iWEF 1.0)

The computation module of iWEF performs three key tasks: (i) determining the consistency of the input pairwise comparison matrix (PCM) of the WEF security indicators, (ii) calculation and normalisation of indices of WEF security indicators by AHP-MCDM technique, and (iii) calculation of the integrated WEF nexus composite index.

8.4.1 Determining the consistency of the input pairwise comparison matrix (PCM)

Judgements and comparisons for the PCM are subjective in real life, it is difficult for the WEF-related stakeholders to make perfectly consistent judgements especially with multiple criteria (e.g., indicators) and under uncertainty. In most cases, decision-makers tend to make random judgements which lead to a random matrix that is expected to be highly inconsistent. Based on the AHP method, the iWEF model computes the consistency ratio (*CR*), which measures the randomness and consistency of the pairwise judgements from the ratio of the consistency index (*CI*) to the randomness index (*RI*). The *CR* value is calculated as in Mu and Pereyra-Rojas (2017):

$$CR = \frac{CI}{RI} \quad \text{(Equation 1)}$$

where: *CI* is the consistency index which measures the degree of inconsistency and irrationality of judgements in PCMs, and *RI* is the randomness index which is a measure of how close the judgements of a PCM are closer to a random matrix depending on the order *n* of the matrix or number of WEF security indicators which is six (6) in iWEF model by Saaty and Vargas (2012).

Average random consistency index (*RI*) (Saaty and Vargas, 2012)

n	1	2	3	4	5	6	7	8	9
Random consistency index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45

n = six (6) WEF security indicators in the case of iWEF model, thus RI = 1.25

If a stakeholder states that "water availability" performs better than "water productivity", and the latter performs better than "energy productivity", their judgements become highly random (high *RI*) and inconsistent (high *CI*) if they mention that "energy productivity" performs better than "water availability".

CI is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad \text{(Equation 2)}$$

where: λ_{max} is the principal or maximum eigen-value estimated by averaging the value of the consistency vector of the PCM, Cv_{ij}, as in Mu and Pereyra-Rojas (2017):

$$\lambda_{max} = \sum_{i=1}^{n} Cv_{ij} \quad \text{(Equation 3)}$$

where: Cv_{ij} is calculated by multiplying the pairwise comparison matrix (C_{ij}) by the weights vector and then dividing the weighted sum vector by criterion weight (W_{ij}) as in Teknomo (2006), Bunruamkaew (2012), and Mu and Pereyra-Rojas (2017):

$$Cv_{ij} = \frac{1}{W_{ij}} \sum_{ij}^{n} C_{ij} W_{ij} \qquad \text{(Equation 4)}$$

Based on the obtained *CR* value, the iWEF model then either accepts if $CR < 0.1$ (or 10%) or rejects it if $CR \geq 0.1$ (Saaty and Vargas, 2012).

8.4.2 Calculation and normalisation of indices of WEF security indicators by Analytical Hierarchy Process Multi-Criteria Decision Making (AHP-MCDM) technique

If the PCM is consistent, i.e., $CR < 0.1$, the iWEF model proceeds to normalise the provided PCM from which it calculates the normalised indices for each indicator and the overall integrated WEF nexus composite index. The iWEF model computes the normalised indices for the six indicators by taking the eigenvector corresponding to the largest eigenvalue of the matrix and then normalising the sum of the components (Nhamo *et al.*, 2020). The overall importance of each indicator is then determined. The PCM of *n* criteria (in this case, 6 indicators of WEF security), is determined using Saaty's scaling ratios in the order ($n \; X \; n$) (in this case $6 \; X \; 6$) (Saaty, 1990). As adopted from Saaty and Vargas (2012), *A* is a matrix with elements $a_{ji,}$ which is the decision maker's preference of the i^{th} criterion (e.g., water availability) over the j^{th} criterion (e.g., water productivity). The matrix's reciprocity is expressed as:

$$PCM = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad \text{(Equation 5)}$$

where: $a_{ij} > 0$; $a_{ij} = \frac{1}{a_{ji}}$

After generating this PCM of WEF security indicators, it is then normalized as a matrix *B* with elements b_{ji}, constructed by dividing each element of the PCM by its column sum and expressed as in Saaty and Vargas (2012):

$$B = \begin{bmatrix} \frac{a_{11}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{12}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{1n}}{\sum_{t=1}^{n} a_{tn}} \\ \frac{a_{21}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{22}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{2n}}{\sum_{t=1}^{n} a_{tn}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{a_{n1}}{\sum_{n=1}^{n} a_{n1}} & \cdots & \cdots & \frac{a_{nn}}{\sum_{t=1}^{n} a_{tn}} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \quad \text{(Equation 6)}$$

Each weight value, i.e., normalised index w_i in matrix of normalised indices *W* is computed by averaging across the rows of *B* as in Saaty and Vargas (2012):

$$W = \frac{1}{n} \begin{bmatrix} \sum_{n=1}^{n} b_{1n} \\ \sum_{n=1}^{n} b_{2n} \\ \cdots \\ \sum_{t=1}^{n} b_{nt} \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} \quad \text{(Equation 7)}$$

where: $\sum_{i=1}^{n} w_i = 1$

8.4.3 Calculation of the integrated WEF nexus composite index

The iWEF model determines the integrated WEF nexus composite index as a weighted average of the normalised indices w_i. In calculating the weighted average, i.e., the integrated WEF nexus composite index, the weights are the integers 1-6 and the lowest weight (1) is assigned to the smallest normalised index while the highest weight (6) is assigned to the largest normalised index. Thus, the value of the integrated WEF nexus composite index ranges from zero (0.048, low) to one (0.286, high).

8.5 Appendix E: Randomly Generated Inconsistent and Consistent Pairwise Comparison Matrices (PCMs) Used for Calibrating Calculations for the Consistency Ratio (CR) in the iWEF Model

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1,00	1,00	1,00	0,33	0,33	1,00
Water productivity	1,00	1,00	3,00	5,00 **(1,00)**	1,00	1,00
Energy accessibility	1,00	0,33	1,00	3,00 **(0,33)**	0,20	0,33
Energy productivity	3,00	0,20 **(1,00)**	0,33 **(3,00)**	1,00	1,00	5,00 **(2,00)**
Food self-sufficiency	3,00	1,00	5,00	1,00	1,00	7,00
Crop productivity	1,00	1,00	3,00	0,20 **(0,50)**	0,14	1,00
Normalised index	1,00	1,00	1,00	0,33	0,33	1,00

Note: Shaded cells represent pairwise comparison of an indicator against itself; Boldened values are for the consistent PCM.

8.6 Appendix F: Pairwise Comparison Matrices (PCMs) for Rankings of WEF Resource Security Indicators (Judgements) by WEF-related Key Expert Stakeholders, and Normalised Indices for IUWMA (unbracketed) and EDM (bracketed) in South Africa

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1.00	1.00 (1.00)	0.20 (0.20)	1/3 (0.20)	0.20 (1/3)	0.20 (0.20)
Water productivity	1.00 (1.00)	1.00	1/3 (0.20)	1/2 (1/3)	1/3 (1/3)	1/3 (0.2)
Energy accessibility	5.00 (5.00)	3.00 (5.00)	1.00	1.00 (3.00)	1.00 (1.00)	3.00 (1.00)
Energy productivity	3.00 (5.00)	2.00 (3.00)	1.00 (1/3)	1.00	1.00 (1/3)	1/3 (1/3)
Food self-sufficiency	5.00 (3.00)	3.00 (3.00)	1.00 (1.00)	1.00 (3.00)	1.00	1/3 (1.00)

Crop productivity	5.00 (5.00)	3.00 (5.00)	1/3 (1.00)	3.00 (3.00)	3.00 (1.00)	1.00
Normalised index	0.049 (0.052)	0.067 (0.054)	0.269 (0.266)	0.154 (0.129)	0.184 (0.232)	0.277 (0.267)

Note: Shaded cells represent pairwise comparison of an indicator against itself.

8.7 Appendix G: Case Study Areas in Zimbabwe

8.7.1 Mzingwane Catchment

Mzingwane Catchment fully encloses seven districts (Beitbridge Rural, Beitbridge Urban, Gwanda Rural, Gwanda Urban, Mangwe, Umzingwane, Matobo), while five districts (Insiza, Plumtree, Chiredzi Rural, Mwenezi, and Mberengwa) have only portions in the catchment. The descending order of provincial portions by population and area in Mzingwane Catchment is Matabeleland South, Masvingo and Midlands (ZimStat, 2023). In the catchment, the coefficient of variation (CV) for rainfall ranges from less than 10% (less) in the area around Beitbridge, through less than 30% (moderate) in the southern lowveld and approximately 40% (high) with the probability of more than 500 mm/yr of precipitation being less than 60% in the southern highveld (LIMCOM, 2011; Asfaw *et al.*, 2018).

The common soils in the catchment include moderately weathered and relatively fertile shallower sandy soils (Luvisols), and patches of highly fertile deeper loam soils (Vertisols) and poor shallow, stony soils (Lithosols) in the mountainous areas. The vegetation includes Southern Africa Bushveld (LIMCOM, 2011; LIMCOM *et al.*, 2017). Climate is changing in the catchment and the most vulnerable group in the catchment are rural populations who mainly survive from rainfed subsistence agriculture and heavily depend on ecosystem services such as freshwater, forests and fish (Dickens *et al.*, 2020; GoZ, 2022a; Chisadza *et al.*, 2023). The catchment is susceptible to droughts (once every 7 to 11 years) and extreme droughts (once every 10 to 20 years), with increased probability of crop failure, mainly due to rainfall variability (LIMCOM, 2011). During the period of 1886–1906, the number of rainy days (≥1 mm) decreased by 34%, rainfall intensity concentrated and increased, and the onset and cessation dates of the rainy season notably shifted resulting in a significantly reduced length of the rainy season. Similarly, the frequency of long intra-season dry spells increased. Similarly, discharge in Mzingwane Catchment has declined significantly since 1980, particularly the annual unit runoff, while the days without flow have increased (Love *et al.*, 2010; Dickens *et*

al., 2020; Sibanda *et al.*, 2020b). Global climate models (GCMs) project an average increase in temperatures by 1-2°C and a decrease in rainfall by 68-158 mm per annum by 2080, with risks of less rainy days and more future extreme events by 2100 leading to exacerbated water scarcity by 2050, lower crop yields, increased food shortages, less annual discharge, and stressed urban water supplies (Love *et al.*, 2010; Dickens *et al.*, 2020; Sibanda *et al.*, 2020a).

8.7.2 Umzingwane District

Poverty is high in Umzingwane District at a prevalence rate of 82.1% (GoZ, 2022b). The wards in Umzingwane District are categorized as communal (wards 1-12), resettlement (wards 13, 14, 19, 20 and part of 17), commercial (15, parts of 17 and 18), and peri-urban (ward 16). The latter hosts Esigodini Growth Point which is the district capital (Umzingwane Rural District Council, n.d.). Umzingwane District can be demarcated into two distinct livelihood zones, namely the Matabeleland Middleveld Communal zone (wards 1-12) which live on livestock production, crop production, remittances and petty trading; and the Southern Cattle and Cereal Farming zone (wards 13, 14, 15, 17, 18, 19 and 20) which survive on maize and cattle production (Figure 3a) (GoZ, 2022b). The ecosystem is typically semi-arid savannah with sparsely distributed woodlands species and grass species (Maviza *et al.*, 2022). Climate trends indicate persistent drying, shorter very wet periods with more intense precipitation, and a declining precipitation gradient (Maviza *et al.*, 2022).

The soils in the district are moderately coarse-grained kaolinitic sands (from the granites and Limpopo gneisses); very shallow to moderately shallow clays and loams (derived from the greenstone belts); and very shallow sands, formed from the locally weathered basalts (Maviza and Ahmed, 2020; Maviza *et al.*, 2022).

8.8 Appendix H: Revised Agro-ecological Zones (AEZs IV, Va, Vb) in Mzingwane Catchment and Umzingwane District in Zimbabwe (Manatsa *et al.*, 2020)

AEZ	Climatic conditions				Dominant soil group(s)	Recommended / ideal land-use
	P_{annual} (mm)	p(P>500) (%)	P_{length} (days)	T_{max} (°C)		
III	650 – 800	75 - 80	110 - 120	25 - 28	Fersiallitic	Suitable for maize (varieties maturing in 110–120 days), soybean, groundnuts, cotton, sunflower, semi-intensive livestock production (beef, dairy, goats, poultry). Crop production requires supplementary irrigation.
IV	450 – 650	60 - 80	105 - 120	27 - 29	Fersiallitic; sporadic sodic, lithosol and siallitic	Ideal: extensive cattle ranching, small livestock (e.g., goats and poultry), wildlife. Irrigation: maize varieties maturing in 105-120 days. Rainfed: drought tolerant crops e.g., sorghum, finger millet, pearl millet, watermelons, cowpeas.
Va	<650	60 - 80	100 – 120	28 - 30	Fersiallitic; sporadic vertisol and siallitic	Ideal: extensive cattle ranching, goat production, game-ranching, tourism. Irrigation: sugarcane, tree plantations, mainly oranges, lemons and lime. Marginal: drought tolerant crops e.g., sorghum, finger millet, pearl millet. cowpeas.
Vb	<600	<60	<110	28 - 32	Siallitic; sporadic sodic and regosols	Ideal: extensive cattle ranching, goats wildlife tourism Irrigation: tree plantations, mainly oranges, lemons and lime.

P_{annual} = Annual rainfall (mm); p(P>500) = probability of exceeding 500 mm (%); P_{length} = length of rainfall season (days); T_{max} = maximum temperature (°C).

8.9 Appendix I: Pairwise Comparison Matrices (PCMs) for Rankings of WEF Resource Security Indicators (Judgements) by WEF-related Key Expert Stakeholders, and Normalised Indices for Mzingwane Catchment (unbracketed) And Umzingwane District (bracketed) in Zimbabwe

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1.00	1.00 (0.50)	0.50 (0.50)	2.00 (1.00)	1/3 (0.50)	1.00 (1.00)
Water productivity	1.00 (2.00)	1.00	0.50 (1/3)	2.00 (1.00)	0.50 (0.50)	1.00 (1.00)
Energy accessibility	2.00 (2.00)	2.00 (3.00)	1.00	2.00 (2.00)	2.00 (1.00)	2.00 (2.00)
Energy productivity	0.50 (1.00)	0.50 (1.00)	0.50 (0.50)	1.00	2.00 (0.50)	1.00 (2.00)
Food self-sufficiency	3.00 (2.00)	2.00 (2.00)	0.50 (1.00)	0.50 (2.00)	1.00	2.00 (2.00)
Crop productivity	1.00 (1.00)	1.00 (1.00)	0.50 (0.50)	1.00 (0.50)	0.50 (0.50)	1.00
Normalised index	0.134 (0.112)	0.139 (0.133)	0.265 (0.263)	0.138 (0.140)	0.205 (0.243)	0.119 (0.110)

Note: Shaded cells represent pairwise comparison of an indicator against itself

8.10 Appendix J: CMIP5 SSPs (van Vuuren and Carter, 2014; Calvin *et al.*, 2017; Fricko *et al.*, 2017; Fujimori *et al.*, 2017; Kriegler *et al.*, 2017; O'Neill *et al.*, 2017; Riahi *et al.*, 2017; van Vuuren *et al.*, 2017; Pedersen *et al.*, 2022).

SSP	Narratives
SSP1	Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation). The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals,

	inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	Middle of the Road (Medium challenges to mitigation and adaptation). The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation). A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation). Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech

	economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.
SSP5	Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation). This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

8.11 Appendix K: CMIP5 RCPs (Moss *et al.*, 2010; Masui *et al.*, 2011; Riahi *et al.*, 2011; Thomson *et al.*, 2011; van Vuuren *et al.*, 2011a; van Vuuren *et al.*, 2011b; van Vuuren and Carter, 2014; Pedersen *et al.*, 2022; World Bank, n.d.).

RCP	**Narratives**
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100.
RCP6.0	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100.
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO^2 eq) by 2100.

8.12 Appendix L: SRES scenarios (IPCC, 2000; Nakicenovic *et al.*, 2000; Carter *et al.*, 2001; Abram *et al.*, 2019; Pedersen *et al.*, 2022).

SRES scenario	Cumulative CO_2 emissions 1990–2100	Description (and variants)
A1	Medium–high	Very rapid economic growth, global population peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. Three groups that describe alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
A2	High	A very heterogeneous world, self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, leading to continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	Low	A convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. Emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2	Medium–low	Emphasis is on local solutions to economic, social, and environmental sustainability. Continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. Oriented toward environmental protection and social equity but focuses on local and regional levels.

8.13 Appendix M: CMIP6 SSPX-Y scenarios (O'Neill *et al.*, 2016; Abram *et al.*, 2019; Gidden *et al.*, 2019; Meinshausen *et al.*, 2020; IPCC, 2021; Tebaldi *et al.*, 2021).

SSPX-Y	Forcing category	Target 2100 forcing level (W/m^2)	Scenario type
Tier 1 (top priority)			
SSP5-8.5	High	8.5	Baseline
SSP3-7.0	High	7.0	Baseline
SSP2-4.5	Medium	4.5	Mitigation
SSP1-2.6	Low	2.6	Mitigation
Tier 2 (additional scenarios of interest)			
SSP4-6.0	Medium	6.0	Mitigation
SSP4-3.4	Low	3.4	Mitigation
SSP5-3.4-OS	Overshoot	3.4	Mitigation
SSP1-1.9	Low	1.9	Mitigation

8.14 References

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