FROM THEORY TO PRACTICE: DEVELOPING A CASE STUDY AND GUIDELINES FOR WATER-ENERGY-FOOD (WEF) NEXUS IMPLEMENTATION IN SOUTHERN AFRICA

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Over the last decade, the water-energy-food (WEF) nexus has emerged and gained prominence as an approach for systematically understanding and managing trade-offs and synergies across water, energy and food sectors. Southern Africa has made significant strides to adopt and contextualise the concept for realising regional socio-economic development goals related to sustainable natural resources management, job and wealth creation and achieving WEF securities. The global goal of this project was to develop a water-energy-food (WEF) nexus modelling approach for the African continent, using southern Africa as a case study, that could be used to quantify and interpret the cross-sectoral complexity of resources and support the transformation required to meet the increasing demand for WEF resources in the context of climate change. To achieve this, the project sought to develop a WEF nexus model that integrates and quantifies the relationships among the WEF sectors and assesses whether resource planning and management are sustainable or unsustainable. The model results indicate priority areas needing immediate intervention, as results provide a clear overview of current resource performance. The model would also provide for scenario planning, an assessment of the Sustainable Development Goals and rural livelihoods transformation within the context of the region's socio-economic development goals.

The study and methodology followed a transdisciplinary process-based mixed methodology, which included (i) a state-of-the-art WEF nexus assessment for southern Africa, focusing on WEF nexus status, opportunities, and possible regional case studies for the WEF nexus, (ii) developing an applicable and scalable WEF nexus modelling approach for the region, (iii) applying the model and framework to assess rural livelihoods, and (iv) applying the WEF nexus model for scenario planning and SDG performance assessment.

The literature review highlighted that existing WEF governance was siloed, limiting the capacity to address socio-economic development challenges, which require integrated cross-sectoral considerations. Existing WEF insecurities are exacerbated by climate change, increasing uncertainty for future development plans. These challenges are broadly reflected across southern African member states. Given the complexities, the

WEF nexus approach offers opportunities to effectively achieve sustainable socio-economic development and transformation through cross-sectoral coordination and collaboration at various levels. This would support the attainment of several SDGs, particularly SDGs 2, 6 and 7, with interlinked positive effects on several other SDGs. Operationalising the WEF nexus approach requires commitment from member states, supported by technological innovations that allow attaining WEF securities with no negative environmental impacts while maintaining natural resources for posterity. This calls for a paradigm shift and restructuring of established concepts of sovereignty towards integration and cooperation.

A major focus of the project was developing an applicable and scalable WEF nexus model. To this end, the project built on previous efforts to develop a user-friendly, open access, web-based and GIS-enabled integrative WEF nexus analytical model, iWEF. The iWEF model is GIS-enabled through a 'hard-linked' GIS integration of the WEF nexus model with open-source base maps. The motivation to make iWEF free and open access was informed by a separate study highlighting that previous models had failed due to them being publicly unavailable. The iWEF model targets users in academia, research, natural resource management, planning, policy- and decision-making. The outputs of iWEF include a spider graph of normalised indices and maps, allowing visualisation of interactions, interdependencies, and inter-connectedness among WEF nexus sectors. The quantitative indices highlight overall and specific performance of the WEF system and its sectors, respectively. The additional maps provide a visualisation of the spatial distribution of the WEF nexus and hotspots in the locations of interest. The iWEF model displays radar charts and map results for multiple case studies, allowing for scenario planning and analysis. Future developments are planned so that indicators in iWEF can reflect both qualitative and quantitative aspects of WEF resources and broaden indicators to include additional dimensions of environment and health. The iWEF model also needs to be further improved and strengthened for its abilities of scenario planning so that it can guide on planning, implementation and monitoring of robust nexus-friendly interventions and investments.

Using regional-level indicators, the project also developed a WEF Nexus Analytical Livelihoods Framework (ALF), which was applied to assess the WEF nexus' potential to inform rural livelihoods transformation at a regional level. The analysis highlighted the unsustainability of current resource utilisation and management, confirming trade-offs caused by siloed sectoral approaches. While well-intentioned to address food security, the focus on food self-sufficiency, if not balanced with cross-sectoral considerations, creates unintended risks to rural household food security and well-being. Applying the WEF Nexus ALF provided insights into sustainable natural resources management, building resilience and well-being in rural areas through attaining WEF securities. In doing so, the study confirmed the utility of the WEF nexus as an inclusive, transparent, intergovernmental approach for all stakeholders and as a decision-support tool for informing holistic and systematic development agendas. The link between WEF and SDG indicators provides an opportunity for further studies on assessing the performance of related SDGs using the WEF nexus analytical model.

As SDGs are assessed through targets to be achieved by 2030 and monitored through measurable indicators, this project applied the WEF nexus modelling approach to assess progress towards SDGs using South Africa as a case study. The study highlighted pathways to ensure socio-ecological sustainability and environmental health by establishing the interlinkages between several SDGs and nexus approaches. These linkages facilitate sustainable natural resources management and balance cross-sectoral trade-offs and synergies. The connectedness of current challenges (climate change, population growth, migration, and the emergence of novel infectious diseases) requires holistically transformative approaches that address these cross-cutting challenges. Managing the intricate relationships between distinct but interconnected sectors through nexus planning has provided decision-support tools to formulate coherent strategies that drive resilience and sustainability. The established linkages between nexus planning and SDGs could strengthen cross-sectoral collaboration, cooperative governance and management through evidence-based interventions. As food production, water provision, and energy accessibility are the major socio-economic and environmental issues currently attracting global attention; the methodology promotes attaining sustainability by 2030.

The imbalance between resource availability and population increase requires transformative approaches to inform policy, decision-making and practice on coherent adaptation strategies for improved livelihoods and resilient communities. This project applied WEF nexus analytical model to holistically assess resource availability, distribution, use and management locally in Sakhisizwe Local Municipality, South Africa. The aim was to inform policies and decisions on improving resource-poor rural communities' livelihoods. The analysis simplified the relationship between the intricately interlinked socio-ecological components and facilitated the identification of priority areas for intervention. The study confirmed the utility of the WEF nexus approach for informing decisions on improving livelihoods, enhancing resource securities, identifying priority areas for intervention and providing transformative pathways towards sustainable development.

Having addressed objectives related to developing an applicable and scalable WEF nexus modelling approach and applying it to assess rural livelihoods and SDG performance assessment, a subsequent objective was to propose an approach for developing WEF nexus scenarios. This study adopted a systematic literature review on WEF scenario planning using the PRISMA protocol. Specifically, we focus on WEF nexus drivers of change, scales (spatial and temporal), analytic tools, pathways, stakeholder engagement and roadmaps. Few studies have applied scenario planning in the WEF nexus approach. They considered major drivers of change, including climate change, social, economic, environmental, land use and technological. Long-term planning horizons dominated in WEF nexus scenario planning; this is desirable for sustainable development planning. Various analytic models were applied for analysing resources and their nexus, while studies considered globally established pathways, cross-cutting interventions, and measures for managing the supply and demand of WEF resources. The updated Coupled Model Intercomparison Project Phase 6 (CMIP6) SSP-RCP pathways need to be considered for relevance in WEF nexus scenario planning. Similarly, there is scope for including RAPs to capture the evolution of agricultural development in exploring integrated WEF nexus future scenarios. The findings from the literature review also guided us to develop a generic stakeholder-driven and science-based (i) flexible integrative framework and (ii) iterative roadmap for co-planning of WEF nexus scenarios. We envisage the review, proposed framework, and roadmap to guide and inform nexus investment dialogues for planning WEF systems that are robust, resilient and sustainable across generations.

Conclusion and Recommendations

The project was successful in developing, testing and applying a WEF nexus modelling approach at various scales, from regional (southern Africa) to national (South Africa) and local (Sakhisizwe Municipality). In doing so, we demonstrated the applicability of the WEF nexus approach at various scales. Additionally, applying the WEF nexus model to assess progress towards the SDGs provided a unique opportunity to demonstrate the WEF nexus approach's suitability for informing policy and decision-making. The initial work on developing WEF nexus scenarios is an important milestone as it will broaden the applicability of the WEF nexus approach. The fact that WEF nexus tools do not have predictive capability restricts their application to status quo assessments and identification of areas for intervention. With the inclusion of scenarios, the iWEF model could be applied for strategic decision-making and assessing sustainability pathways. Future work should focus on improving existing WEF nexus tools such as the iWEF model, generating WEF nexus case studies for evidence, and assessing actual interventions/projects/plans. This will aid in practicalising the WEF nexus approach. In addition, the uptake and adoption of the WEF nexus approach will rely on the sufficient capacity to embed and drive the approach. A current major limitation is the lack of capacity at all levels. This should be a priority for future research for development.

Innovation

The project contributed to the development of two WEF nexus models, (i) the WEF Nexus Analytical Livelihoods Framework (ALF) and (ii) the iWEF model, which was built on the integrative analytical model. In addition, the project has contributed to the development of WEF nexus scenarios, setting an important platform for future WEF nexus research. The development of the iWEF model and WEF nexus scenarios provides an opportunity to develop integrated development pathways, further pushing the WEF nexus from theory to practice. The project also contributed significantly to knowledge products through the WEF Nexus Narratives book[1].

[1] Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G, and Massawe, F. 2022. Water-Energy-Food Nexus Narratives and Resource Securities: A Global South Perspective. Elsevier. DOI: 10.1016/C2020-0-03951-4

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LIST OF ABBREVIATIONS

ABM	Agent-Based Modelling
ADF	Agricultural Development Fund
AHP	Analytic Hierarchy Process
AHP-OS	AHP Online System
ALF	Analytical Livelihoods Framework
APSIM	Agricultural Production Systems Simulator
ARWR	Actual Renewable Water Resources
AUC	African Union Commission
AWEFSM	Agricultural Water-Energy-Food Sustainable Management model
BAU	Business-As-Usual
CAADP	Africa Comprehensive Africa Agricultural Development Programme
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact
CC	Climate Change
CI	Consistency Index
CityGML	City Geography Markup Language
CLD	Causal Loop Diagram
CLEWs	Climate-, Land-, Energy- and Water-systems
CMI	Climate Moisture Index
CMIP	Coupled Model Intercomparison Project
CR	Consistency Ratio
CSMs	Crop Simulation Models
CSOs	Civil Society Organisations
CSS	Cascading Style Sheets
CTC	Central Transmission Corridor
DAFNE	Decision-Analytic Framework to explore the water-energy-food NExus
DNA	National Directorate of Water
DRC	Democratic Republic of Congo
DSSAT	Decision Support System for Agro-technology Transfer
DWS	Department of Water and Sanitation
ENSO	El Niño Southern Oscillation
EPA	United States Environmental Protection Agency
EPAT	Energy Portfolio Assessment Tool
EPIC	Environmental Policy Integrated Climate Model
ETHZÜRICH	SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH
EU	European Union

FANR	Food, Agriculture and Natural Resources
FAO	Food and Agriculture Organisation of the United Nations
FCM	Fuzzy Cognitive Mapping
FEWCalc	Food-Energy-Water Calculator
GAEZ	Global Agro-Ecological Zones
GCAM	Global Change Assessment Model
GCWM	Global Crop Water Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GLOBIOM	Global Biosphere Management Model
GPS	Global Positioning System
GREAT for FEW	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus
GUI	Graphical User Interface
GWP	Global Water Partnership
GWPSA	Global Water Partnership Southern Africa
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HTML	HyperText Markup Language
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IBRD	International Bank for Reconstruction and Development
IDP	Integrated Development Plan
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
ILRI	International Livestock Research Institute
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
INCA	Integrated Catchment Model
INGOs	International Non-Governmental Organizations
IPCC	Intergovernmental Panel on Climate Change
IRBs	International River Basins
IRENA	International Renewable Energy Agency
iWEF	Web-based and GIS-enabled integrative WEF nexus analytical (iWEF) model
IWRM	Integrated Water Resources Management
LCA	Life-Cycle Assessment
LHDA	Lesotho Highlands Development Authority
LHWC	Lesotho Highlands Water Commission
LHWP	Lesotho Highlands Water Project
LIMCOM	Limpopo Watercourse Commission

LIVSIM	LIVestock SIMulator
LPG	Liquefied Petroleum Gas
LPJmL	Lund-Potsdam-Jena model
MCDM	Multi-Criteria Decision Making
MEA	Millennium Ecosystem Assessment
MS	Microsoft
MuSIASEM	Multiple-Scale Integrated Assessments of Societal Metabolism
NDCs	Nationally Determined Contributions
NDP	National Development Plan
NEST	Nexus Solutions Tool
NGOs	Non-Governmental Organizations
NPC	National Planning Commission
OECD	Organisation for Economic Co-operation and Development
OGC	Open Geospatial Consortium
OKACOM	Okavango River Basin Commission
ORASECOM	Orange-Senqu River Commission
OSeMOSYS	Open Source Energy Modelling Systems
PCM	Pairwise Comparison Matrix
PICOS	Population, Indicator, Comparison, Outcome and Study
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RAP	Regional Agriculture Policy
RAPs	Representative Agricultural Pathways
RBOs	River Basin Organisations
RCP	Representative Concentration Pathway
REASAP	Regional Energy Access Strategic Action Plan
RESAP	Renewable Energy Strategy and Action Plan
RI	Randomness Index
RIDMP	Regional Infrastructure Development Master Plan
RISDP	Regional Indicative Strategic Development Plan
RSAP	Regional Strategic Action Plan
SACREEE	SADC Centre for Renewable Energy and Energy Efficiency
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
SARDC	Southern African Research and Documentation Centre
SAS	Story And Simulation
ScenarioMIP	Scenario Model Intercomparison Project
SDGs	Sustainable Development Goals
SDM	System Dynamics Modelling
SEI	Stockholm Environment Institute
SPARROW	Spatially Referenced Regressions on Watershed attributes model

SPHY	Spatial Processes In Hydrology
SRES	Special Report on Emissions Scenarios
SSL	Secure Sockets Layer
SSP	Shared Socioeconomic Pathway
StatsSA	Statistics South Africa
SWAT	Soil and Water Assessment Tool
TOA-MD	Trade-off Analysis Model for Multi-dimensional Impact Assessment
TOC	Theory of Change
TV	Television
UCEC	Urban Circular Economy Calculator
UK	United Kingdom
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNGA	United Nations General Assembly
UNICEF	United Nations Children's Fund
USA	United States of America
WASH	Water-Sanitation and Health
WCRP	World Climate Research Programme
WEAP-LEAP	Water Evaluation and Planning System – Long-Range Energy Alternatives Planning System
WEC	World Energy Council
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Environment
WEFSiM	Water-Energy-Food (WEF) nexus Simulation Model
WEFWI	World Economic Forum Water Initiative
WEM	Water-Unemployment-Migration
WFP	World Food Programme
WHAT-IF	Water, Hydropower, Agriculture Tool for Investment and Financing
WHEN	Water-Health-Environment-Nutrition
WHO	World Health Organisation
WoS	Web of Science
WRC	Water Research Commission of South Africa
ZAMCOM	Zambezi River Basin Commission
ZESA	Zimbabwe Electricity Supply Authority
ZESCO	Zambia Electricity Supply Corporation
ZIZABONA	Zimbabwe-Zambia-Botswana-Namibia
ZRA	Zambezi River Authority
ZTK	Zambia-Tanzania-Kenya

LIST OF SYMBOLS

GDP	Gross domestic product
GDP/MJ	Gross domestic product per megajoule
GWh	Gigawatt hours
ha	Hectare
kg	Kilogramme
kg/ha	Kilogrammes per hectare
km^2	Square kilometres
km^3	Cubic kilometres
m^3	Cubic metre
m^3/capita	Cubic metres per capita
MJ	Megajoule
mm	Millimetre
MW	Megawatt
TWh	Terawatt hours per year
W/m^2	Watts per square metre
\$/m^3	United States of America dollars per cubic metre
λ_{max}	Principal or maximum eigenvalue
°C	Degrees Celsius

REPOSITORY OF DATA

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1 INTRODUCTION

The water-energy-food (WEF) nexus has gained increasing attention in the research and decision-making communities in recent years, as evidenced by the increasing number of research activities and published work on the subject. The attention to the WEF nexus is also evidence of the importance of the concept, as ignorance of the interlinkages among WEF sectors will continue causing unforeseen and adverse consequences (Garcia and You, 2016; Weitz *et al.*, 2017). The systematic thinking embedded in the WEF nexus is priceless as it considers the synergies and trade-offs in resource planning, utilisation and management. The developments in one of the three WEF sectors should always consider the impacts on the other two to avoid transferring problems from one sector to the other. A good example is biofuel, in which rapid bioenergy development was initially advocated to mitigate climate change by shifting away from fossil fuels. Still, it has been discovered that it has the potential to cause biodiversity loss and food crisis through land use changes, as biomass crops may compete with food crops for water and land (Meehan *et al.*, 2010). Similar cases can also be found in technology applications where adopting water-conserving irrigation and desalination technologies may create pressures in the energy sector through intensive energy consumption. Adopting the WEF nexus helps identify these trade-offs as it is a planning and decision support tool that guides decision-making on what, why, how and when an intervention must be made. It indicates and provides evidence on priority areas for intervention for sustainable development, improved livelihoods and resource availability at all times (Nhamo *et al.*, 2018).

The challenges faced by the African continent require a systems and transformative approach such as the WEF nexus and a shift from the present 'silo' thinking to one that is cross-sectoral if ever the continent is to meet its set targets premised in the Comprehensive Africa Agriculture Development Programme (CAADP) and the Regional Indicative Strategic Development Plan (RISDP). The continent is faced with some megatrends that include climate change, land degradation, migration, steep population growth (expected to reach 2 billion by 2050), unparalleled urbanisation, diversifying and changing diets and increased consumer demands due to improved standards of living (Awumbila, 2017). These drivers are exerting pressure on already depleted resources, which poses the greatest threat to attaining the 2030 Global

Agenda on Sustainable Development Goals. The WEF nexus sustainably manages resources and ensures sustainability (de Sherbinin *et al.*, 2007).

However, besides the envisaged importance of the WEF nexus, it has remained a rhetoric ambition lacking analytical tools to address the three interlinked global security concerns of access to water, sustainable energy and food security. This major gap remains to turn the nexus into a fully-fledged operational framework (Albrecht *et al.*, 2018). For this reason, the concept has been criticised for lack of clarity and practical applicability (Cairns and Krzywoszynska, 2016), and some have even branded it a repackaging of the Integrated Water Resources Management (IWRM) (Benson *et al.*, 2015). The criticisms have been substantiated by the considerable amount of literature that has been published highlighting the importance of the WEF nexus as a conceptual framework and as a discourse, but lacking analytical tools that can be used to provide real-world solutions (Liu *et al.*, 2017; Mpandeli *et al.*, 2018; Nhamo *et al.*, 2018; Terrapon-Pfaff *et al.*, 2018). Therefore, what remains with the WEF nexus are methods to evaluate synergies and trade-offs integrated and decision support tools that can prevent conflicts, reduce investment risks and maximise economic returns (Howells *et al.*, 2013; Liu *et al.*, 2017). Existing tools that have been developed lack these main attributes and most of them either remain theoretical or maintain a sectoral approach to resource management (Albrecht *et al.*, 2018). This has limited the adoption of current tools apart from being complex or difficult to replicate, and sector integration to establish the linkages among the sectors is unclear or not established at all (McGrane *et al.*, 2019). For the WEF nexus to be a true nexus, it needs a decision support tool that assesses the three sectors as a whole or unitarily, eliminating a "siloed" approach in resource planning, utilisation and management. There is a need for an integrated WEF nexus tool capable of holistically assessing resource development and utilisation (Shannak *et al.*, 2018; McGrane *et al.*, 2019).

Focus concerning the WEF nexus should therefore be directed towards transforming the approach into a decision support tool that provides evidence to policy and decision-making. In February 2020, the Water Research Commission of South Africa (WRC)-funded research project WRC CON2019/2020-00007 entitled: "From theory to practice: developing a case study and guidelines for Water-Energy-Food (WEF) nexus implementation in southern Africa" was awarded to the Project Team, based at the

School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal (UKZN) in Pietermaritzburg.

The study sought to develop a WEF nexus model that integrates and quantifies the relationships among the WEF sectors and assesses whether resource planning and management are sustainable or unsustainable. The model results indicate priority areas needing immediate intervention, as results provide a clear overview of current resource performance. The model would also provide resources for scenario planning, an assessment of SDGs performance, livelihoods analysis and project appraisal. The study and methodology followed a clear path on the WEF nexus work and research that has been done previously by the multi-disciplinary project team.

In the context of South Africa, the research project sought transformation and redress, sustainable development, empowerment of communities, informing policy and decision-making, human capital development, and the generation of new products and services for economic development. Over the three years, a total of 9 deliverables are due to the WRC, which address six (6) specific objectives of the project.

1.1 Objectives

The contractually specified objectives of the project were:

1.1.1 General objective

To develop a nexus modelling approach for the African continent that can be used to explain and interpret the cross-sectoral complexity of resources and support the transformation required to meet the increasing demand for WEF resources in the context of climate change.

1.1.2 Specific objective

Specific objective 1: Conduct a state-of-the-art WEF nexus assessment for southern Africa, focusing on WEF nexus status, opportunities, and possible regional case studies for the WEF nexus.

Specific objective 2: Develop an applicable and scalable WEF nexus modelling approach for the region applicable at any spatial scale.

Specific objective 3: Apply the model and framework to assess rural livelihoods, health and wellbeing at various scales.

Specific objective 4: Apply the WEF nexus model for scenario planning and SDG performance assessment.

Specific objective 5: Apply the model and framework to develop recommendations for implementing the WEF nexus and propose a suitable application scale.

Specific objective 6: Link WEWF nexus with Sustainable Development Goals (SDGs).

All the contractually stated objectives were achieved and form the basis of this research report.

1.2 Scope of the report

This document is the final WRC CON2019/2020-00007 project report. The report is written in a series of self-contained chapters with different authors. Each Chapter addresses at least one of the project's specific objectives as set out in terms of reference. Due to the paper format used, the report does not have a general methodology section; each Chapter has its specific methodology. This may have inadvertently created cases of minor repetition, especially in the methodology section.

The report is structured to address the project objectives of the study in a logical framework.

A general overview of the report is provided below.

Chapter 1: provides a general introduction, background and conceptualisation of the entire study. It motivates the broad study as set out in terms of reference. It also sets out the project's aims and specific objects defined in the contract.

Chapter 2: provides a state-of-the-art review of the WEF nexus for SADC. It presents an overview of regional WEF-related policies, laws, strategies and institutional arrangements to identify any linkages and recommend strategies to undo sectoral approaches towards resource management.

Chapter 3: provides an overview of the development of the web-based and GIS-enabled integrative WEF nexus analytical (iWEF) software package. It explains how the iWEF model was developed and tested.

Chapter 4: provides an analytical livelihoods framework for assessing rural livelihoods. It presents findings from applying the WEF nexus analytical framework for improving rural livelihoods and climate change adaptation in southern Africa.

Chapter 5 presents the WEF nexus analytical framework's application to assess the SDGs' performance. It provides findings from applying the nexus planning model to monitor and evaluate progress towards SDGs using South Africa as a case study. The chapter also highlighted pathways to ensure socio-ecological sustainability and environmental health by establishing the connectivity between SDGs and nexus approaches.

Chapter 6: presents the application of the WEF nexus analytical framework to assess socio-economic development planning at a local level. It provides findings from applying the WEF) nexus analytical model to assess resource availability, distribution, use and management holistically.

Chapter 7: describes the process for developing WEF nexus scenarios based on SSP, RCPs and RAPS. It reviews how scenario planning was previously embedded in the WEF nexus approach. The chapter also proposes a generic framework/approach and roadmap for guiding the WEF nexus scenario planning process.

Chapter 8: provides a holistic discussion of the entire project and links all the separate studies to achieving the project objectives. The chapter also provides the conclusion and recommendations for future studies.

2 LITERATURE REVIEW

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2.1 Background and rationale

The water-energy-food (WEF) nexus has gained increasing attention in the research and decision-making communities in recent years, as evidenced by the increasing number of research activities and published work on the subject. The attention to the WEF nexus is also evidence of the importance of the concept, as ignorance of the interlinkages among WEF sectors will continue causing unforeseen and adverse consequences (Garcia and You, 2016; Weitz *et al.*, 2017). The systematic thinking embedded in the WEF nexus is priceless as it considers the synergies and trade-offs in resource planning, utilisation and management. The developments in one of the three WEF sectors should always consider the impacts on the other two to avoid transferring problems from one sector to the other. A good example is biofuel, in which rapid bioenergy development was initially advocated to mitigate climate change by shifting away from fossil fuels. Still, it has been discovered that it has the potential to cause biodiversity loss and food crisis through land use changes, as biomass crops may compete with food crops for water and land (Meehan *et al.*, 2010). Similar cases can also be found in technology applications where adopting water-conserving irrigation and desalination technologies may create pressures in the energy sector through intensive energy consumption. Adopting the WEF nexus helps identify these trade-offs as it is a planning and decision support tool that guides decision-making on what, why, how and when an intervention must be made. It indicates and provides evidence on priority areas for intervention for sustainable development, improved livelihoods and resource availability at all times (Nhamo *et al.*, 2018).

The challenges faced by the African continent require a systems and transformative approach such as the WEF nexus and a shift from the present ‘silo’ thinking to one that is cross-sectoral if ever the continent is to meet its set targets premised in the

Comprehensive Africa Agriculture Development Programme (CAADP) and the Regional Indicative Strategic Development Plan (RISDP). The continent is faced with some megatrends that include climate change, land degradation, migration, steep population growth (expected to reach 2 billion by 2050), unparalleled urbanisation, diversifying and changing diets and increased consumer demands due to improved standards of living (Awumbila, 2017). These drivers are exerting pressure on already depleted resources, which poses the greatest threat to attaining the 2030 Global Agenda on Sustainable Development Goals. The WEF nexus sustainably manages resources and ensures sustainability (de Sherbinin *et al.*, 2007).

However, besides the envisaged importance of the WEF nexus, it has remained a rhetoric ambition lacking analytical tools to address the three interlinked global security concerns of access to water, sustainable energy and food security. This major gap remains to turn the nexus into a fully-fledged operational framework (Albrecht *et al.*, 2018). For this reason, the concept has been criticised for lack of clarity and practical applicability (Cairns and Krzywoszynska, 2016), and some have even branded it a repackaging of the Integrated Water Resources Management (IWRM) (Benson *et al.*, 2015). The criticisms have been substantiated by the considerable amount of literature that has been published highlighting the importance of the WEF nexus as a conceptual framework and as a discourse, but lacking analytical tools that can be used to provide real-world solutions (Liu *et al.*, 2017; Mpandeli *et al.*, 2018; Nhamo *et al.*, 2018; Terrapon-Pfaff *et al.*, 2018). Therefore, what remains with the WEF nexus are methods to evaluate synergies and trade-offs integrated and decision support tools that can prevent conflicts, reduce investment risks and maximise economic returns (Howells *et al.*, 2013; Liu *et al.*, 2017). Existing tools that have been developed lack these main attributes and most of them either remain theoretical or maintain a sectoral approach to resource management (Albrecht *et al.*, 2018). This has limited the adoption of current tools apart from being complex or difficult to replicate, and sector integration to establish the linkages among the sectors is unclear or not established at all (McGrane *et al.*, 2019). For the WEF nexus to be a true nexus, it needs a decision support tool that assesses the three sectors as a whole or unitarily, eliminating a "siloed" approach in resource planning, utilisation and management. There is a need for an integrated WEF nexus tool capable of holistically assessing resource development and utilisation (Shannak *et al.*, 2018; McGrane *et al.*, 2019). Focus concerning the WEF nexus should therefore be directed towards transforming the approach into a decision support tool that provides evidence to policy and decision-making.

2.2 Introduction

2.2.1 What is the water-energy-food (WEF) nexus?

The three sectors of water, energy and food are strongly linked (Figure 2.1) as food production needs water and energy; water management (extraction, treatment, and redistribution) requires energy; and energy production requires water (Bazilian *et al.*, 2011; Hettiarachchi and Ardakanian, 2016; Mabhaudhi *et al.*, 2016; Rasul, 2016).

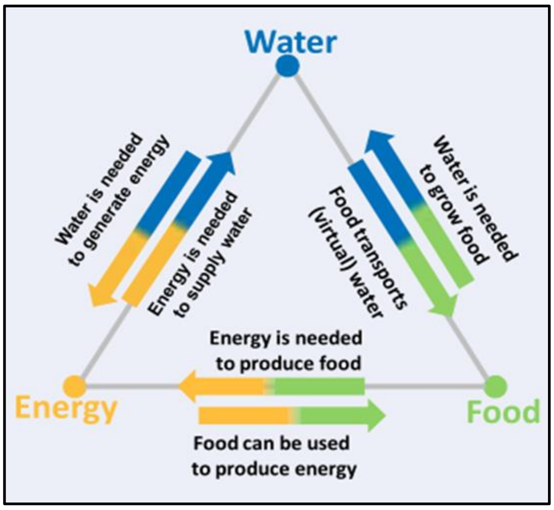

Figure 2.1: The WEF nexus connectivity.

Source: (Hettiarachchi and Ardakanian, 2016)

Any impact on one affects the other two. This interconnection is known as the water-energy-food (WEF) nexus (Leck *et al.*, 2015; Mabhaudhi *et al.*, 2016). Published evidence of the three-way mutual interactions among the WEF nexus components started in 2008 (Hellegers *et al.*, 2008) and has since grown into an important subject (Scott *et al.*, 2015). The WEF Nexus then became prominent at the World Economic Forum in 2011, where it was proposed as an approach for achieving and managing sustainable economic development. Today, the WEF nexus has become a mantra in sustainability circles as the world increasingly recognises the importance of these three fundamental sectors as inextricably interconnected (Alagh, 2010; Martin and Fischer, 2012; Mabhaudhi *et al.*, 2016). It has grown to be an essential approach in achieving the Sustainable Development Goals (SDGs) on poverty eradication, zero hunger, provision of water and sanitation, and access to affordable and reliable energy (Goals 1, 2, 6 and 7, respectively). However, besides the known importance, the WEF nexus remains a rhetoric ambition without proper implementation, monitoring and evaluation guidelines (Rees, 2013; Leck *et al.*, 2015). Most nexus initiatives have focused on sectoral development due to a lack of guidelines and scientific evidence, resulting in unintended consequences (WEF, 2011).

2.2.2 The challenges

Ensuring water, energy, and food security has dominated the development agenda of southern African countries, centred on improving livelihoods, building resilience and regional integration (Davidson *et al.*, 2003; Cervigni *et al.*, 2015). However, regional development targets have remained elusive due to sectoral approaches to resource management, which inadvertently creates an imbalance in resource allocation (Mabhaudhi *et al.*, 2016). The challenge of essential resource insecurity in southern Africa is exacerbated by climate change in a region already classified as a climate hot spot, as the recurrence of drought and flooding increases in intensity and frequency (Conway *et al.*, 2015). This is particularly concerning for the southern African region due to its dependence on climate-sensitive sectors of agriculture and energy, which heavily depend on water resources. WEF resources are vital for human well-being, poverty reduction and sustainable development, and their management is vital to achieving the Sustainable Development Goals (Flammini *et al.*, 2014). Thus, in southern Africa, the WEF nexus approach has the potential to integrate strategies aimed at adapting to the challenges brought about by population growth, rapid urbanisation, increased consumption demands due to improved living standards, and climate change and variability (Figure 2.2) (Beddington, 2009).

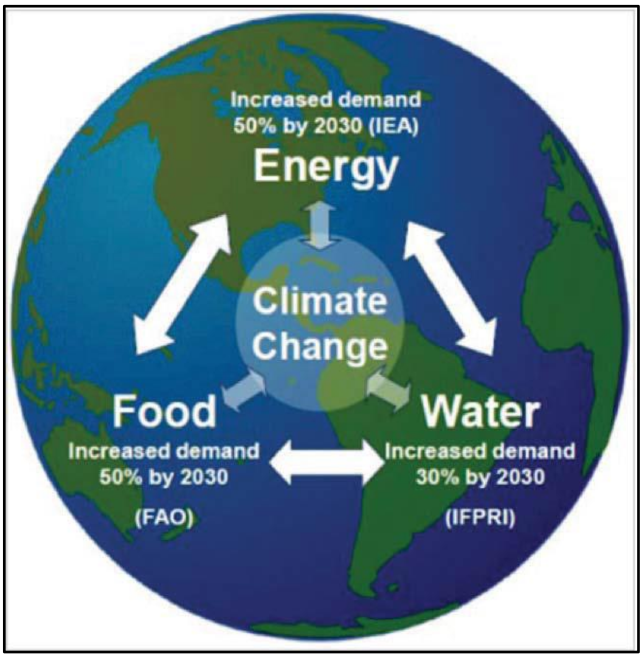

Figure 2.2: The WEF nexus sectoral challenges.
Source: Beddington (2009)

Such integration would translate to savings from costs associated with duplication, increased efficiencies due to streamlining activities, and a higher likelihood of success due to consideration of WEF nexus trade-offs and synergies. However, to achieve this and implement the WEF nexus, transformation is needed to bring about institutional change, alignment, and joint implementation by the public and private sectors.

The pressure to produce more crops and energy requires an integrated approach to balance these competing demands for water resources to ensure socio-economic security, maximise benefits and promote inclusive economic development (Leck *et al.*, 2015; Scott *et al.*, 2015). As the three sectors are inextricably linked, current uncoordinated management has created imbalances in inclusive development and resource allocation (Flammini *et al.*, 2014). Thus, the WEF nexus provides an opportunity to stabilise competing demands and promote regional integration, particularly in southern Africa, where resources are transboundary. With the impressive socio-economic developments in some parts of the region, as well as the impacts of climate change, the pressure on water, energy and food resources continues to increase, requiring coordinated and integrated approaches for sustainable development (Bhaduri *et al.*, 2015; Zaman *et al.*, 2017). The WEF nexus approach can help to ensure that the development of one of the sectors has minimum impacts on the other (Jacobs and Nienaber, 2011; Prasad *et al.*, 2012).

2.2.3 Implementation of the water-energy-food (WEF) nexus

Besides the well-documented and established connectivity of WEF nexus components, the planning and management of the three sectors often fall under different institutions. Consequently, the frameworks that guide them (policies, laws and strategies) often do not link to each other, particularly in southern Africa (Jacobs and Nienaber, 2011; Conway *et al.*, 2015; Mabhaudhi *et al.*, 2016). Current policies and institutions are designed to operate in silos, causing a slowdown in inclusive development. Focusing on the development and management of one sector constrains the development of the others, negatively impacting sustainable development (Mabhaudhi *et al.*, 2016). In the case of the southern African region, the WEF nexus concept demands greater coordination and the recognition of the trade-offs and synergies that exist across the sectors (Rasul, 2016). Sectoral collaboration is particularly relevant in southern Africa as watercourses and electricity grids are shared among countries (Mabhaudhi *et al.*, 2016). Cooperation and collaboration in using and developing these resources cement integration and prevent conflicts (Mabhaudhi *et al.*, 2016; Rasul, 2016). Adopting the WEF nexus at the regional level is essential in southern Africa as the demand for water, energy and food is increasing due to population increase, rapid urbanisation and economic development (Prasad *et al.*, 2012).

2.2.4 The WEF nexus in the context of the southern Africa region

About 60% of the population of southern Africa (Angola, Botswana, Comoros, D.R Congo, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe) live in rural areas relying on rainfed agriculture, lacking basic services of clean energy, water and sanitation, yet the region is endowed with vast natural resources (Nhamo, 2015; van Koppen *et al.*, 2015). The WEF nexus, thus, presents opportunities for integrated resource management for regional integration and inclusive socio-economic development and security as resources are transboundary. The present resource management, often done in silos and at a national level, inadvertently contributes to the region’s failure to meet its development targets, exacerbating its vulnerabilities. The WEF nexus addresses the challenge of sectoral management of resources through adopting harmonised institutions and policies and setting targets and indicators to implement and assess resource management for sustainability. In southern Africa, the WEF nexus could prove valuable by promoting inclusive development and transforming vulnerable communities into resilient communities.

The region's resource-rich 15 transboundary river basins (IRBs) (Figure 2.3 and Table 2.1) present opportunities for coordinated and sustained growth and ensure socio-economic security through the WEF nexus.

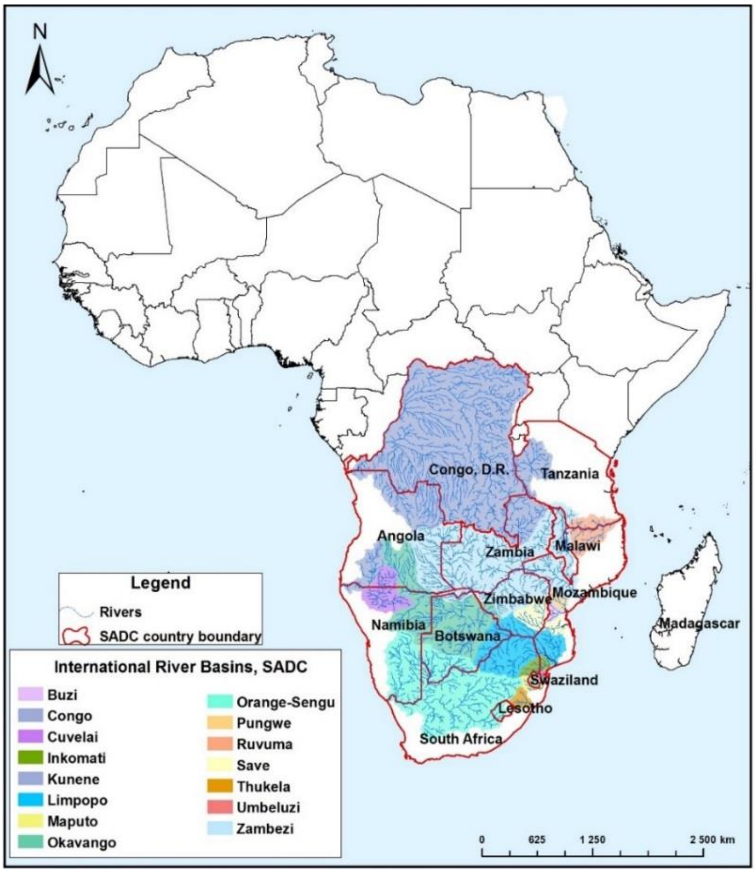

Figure 2.3: SADC countries in Africa and the transboundary river basins within the regional bloc

Table 2.1: Southern Africa transboundary river basins (IRBs) and the riparian states

River Basin	Riparian States	Area (km^2)
Buzi	Mozambique, Zimbabwe.	27,000
Congo	Angola, Democratic Republic of Congo, Tanzania, Zambia	3,800,100
Cuvelai	Angola, Namibia	167,000
Incomati	Mozambique, South Africa, Swaziland	46,740
Kunene	Angola, Namibia	106,560
Limpopo	Botswana, Mozambique, South Africa, Zimbabwe	408,000
Maputo	Mozambique, South Africa, Swaziland	29,970
Nile	Democratic Republic of Congo, Tanzania	3,200,000
Okavango	Angola, Botswana, Namibia	323,192
Orange	Botswana, Lesotho, Namibia, South Africa	1,000,000
Pungwe	Mozambique, Zimbabwe	31,000
Ruvuma	Malawi, Mozambique, Tanzania	152,000
Save	Mozambique, Zimbabwe	115,700
Umbeluzi	Mozambique, Swaziland	10,900
Zambezi	Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe	1,570,000

Riparian countries could achieve short-and long-term benefits through an integrated and coordinated operation of existing and planned hydropower facilities, cooperative flood management and irrigation development (Mabhaudhi *et al.*, 2016). According to the World Bank, cooperation among riparian countries of the Zambezi Basin has the potential to bring a reasonable balance between hydropower and irrigation investment that could result in stable energy generation of some 30 000 Gigawatt hours (GWh)/year and unlock 774 000 ha of irrigated land (IBRD/WorldBank, 2010). Currently, most large dams in the region are underutilised as they were originally designed for single purposes. However, some, like the Itezhi-Tezhi Dam in Zambia, are being redesigned for multipurpose use for both hydropower and irrigation (Deines *et al.*, 2013). The Kariba Dam was also originally commissioned only for hydropower generation but is now used for aquaculture, urban water supply, tourism, support to national parks and wildlife, lake transportation and mining activities (Nyikahadzoi *et al.*, 2017). Such scenarios create new economic opportunities that promote inclusive growth, job creation and sustainable development. However, these are only a few cases that showcase WEF nexus synergies. Adopting and implementing the WEF nexus at the regional level in southern Africa will minimise conflict among member states, and allow inclusive development and investment, as the nexus promote cross-sectoral policy linkages. As the WEF nexus components are sensitive to climate change, its adoption also promotes resilience building initiatives and would contribute to the region’s climate change response strategies. Thus, the nexus unlocks opportunities for collaboration, boosting regional cooperation and inclusive development through a set of common targets.

The uneven distribution of resources in the region creates uneven demand pressures on raw materials and natural resources. As a result, the water and energy resources demand is concentrated in the region's southern parts. In contrast, the northern parts of the region (for example, the Congo and Zambezi river basins) are endowed with abundant water resources that could sustainably deliver these inputs (IBRD/WorldBank, 2010).

2.3 WEF resource endowment in southern Africa

2.3.1 Water resources

Approximately 75% of the southern Africa region, most of which is in the southern part, is semi-arid to arid with a Climate Moisture Index (CMI) of less than -0.6, receiving less than 650 mm of rainfall per annum. The rest, 25%, mostly occupied by northern countries closer to the Equator, is classified as sub-humid with a CMI of 0.25, receiving between 651 and 2 500 mm of rainfall per annum (Nhamo, 2015). The highly variable rainfall that oscillates between 100 and 2 500 mm per annum (Figure 2.4) indicates the uneven distribution of hydrological resources across the region (Davis, 2011).

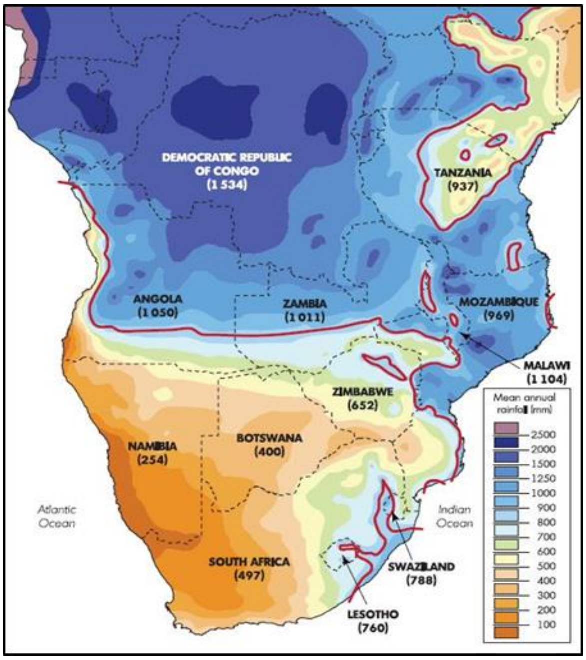

Figure 2.4: Spatial distribution of mean annual rainfall over southern Africa. Source: Ashton, 2008

Seventy-five percent (75%) of the region is classified as water-scarce (physical and economic), mainly due to the uneven distribution of water resources. The mean annual runoff volume of 650 km^3 is substantially low for a region that depends on rainfed agriculture and hydro-power for energy (Nyagwambo *et al.*, 2008). Total renewable freshwater resources are estimated at 2 300 km^3 per annum, of which 76% of water withdrawals are used in agriculture, 16% for domestic and 8% for industrial use (Nhamo, 2015). However, only 5% of available freshwater resources are used (van Koppen *et al.*, 2015). Although agriculture uses the bulk of freshwater resources, crop production remains very low, failing to meet the food requirements of a growing population (Malzbender and Earle, 2007). Seventy percent (70%) of surface water resources are in 15 transboundary river basins (Figure 2.3 and Table 2.1).

The hydrology of southern Africa is thus characterised by the high number of transboundary river basins, 15 in total (Figure 2.3 and Table 2.1). The transboundary nature of the river basins signifies the importance of watercourses in promoting regional integration and development. For example, five southern African countries have water resources dependency ratios of over 50%. They rely on water generated outside their borders to supply more than half of their total water requirements (Malzbender and Earle, 2007; Muller *et al.*, 2015). Figure 2.3 and Table 2.1 demonstrate that over 70% of the region's freshwater resources are shared between two or more member states. Although the southern parts are generally drier, The Congo, Zambezi and Orange-Senqu basins have the potential to generate significant regional benefits through water transfer and hydropower generation (Stiles and Murove, 2015). Although groundwater abstraction has increased in recent years, little is known about the aquifers, most of which are also transboundary (Braune and Xu, 2008). The shared natural resources provide a basis for developing regional instruments to support cooperation in resource management for inclusive development and cement regional integration.

Considering the uneven distribution of hydrological resources in the region and the increasing water demand, it becomes evident that operating at a regional level can increase benefits and reduce risks. A coordinated approach with benefit-sharing mechanisms to manage the region's shared water resources could minimise social costs and improve allocative efficiency. There are also challenges to regional coordination on water, including difficulties with resource mobilization and allocation and the perception that regional processes extend project timelines (WorldBank, 2015; WorldBank, 2016).

2.3.2 Energy resources

The southern Africa region is endowed with vast energy resources (Figure 2.5), although availability varies from country to country (Stiles and Murove, 2015). The untapped potential of hydropower generation in Angola, The DRC, Mozambique and Zambia can supply the whole region with electricity (IBRD/WorldBank, 2010; Stiles and Murove, 2015). Thus, energy, like water resources, can play an important role in regional integration, inclusive economic development and poverty eradication. The region currently shares power grids that generate electricity from shared watercourses (Figure 2.5).

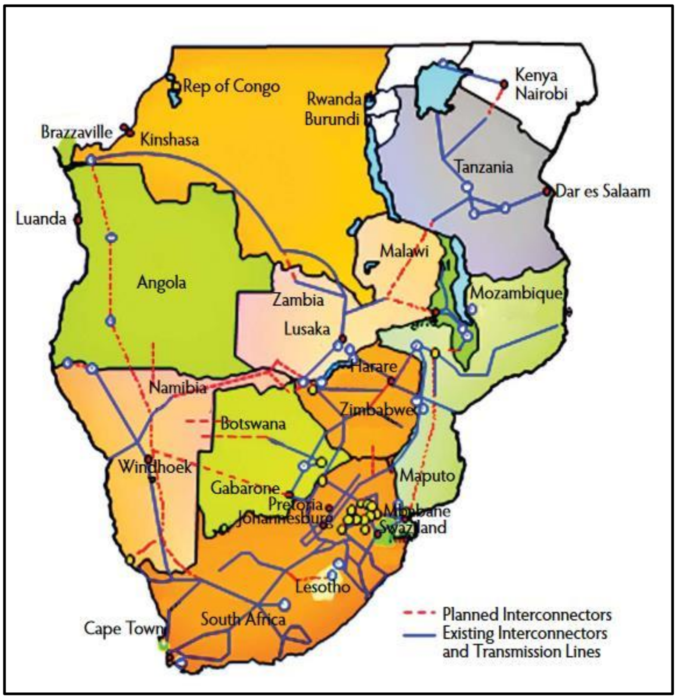

Figure 2.5: Distribution of energy infrastructure in SADC.

Source: SAPP, 2015

However, biomass remains the most used source of energy as only 24% of the total population, and 5% of rural people have access to electricity (Sebitosi and Okou, 2010; Schreiner and Baleta, 2015). Over-dependency on biomass energy has contributed to massive deforestation and desertification in the region (Mabhaudhi *et al.*, 2016). Regional hydropower potential is estimated at 1 080 terawatt-hours per year (TWh/year), but the current level of exploitation is less than 31 TWh/year (Stiles and Murove, 2015). In recognition of the need for regional coordination, the southern Africa region formed the Southern African Power Pool (SAPP) in 1995 as an initiative to support and strengthen regional cooperation and infrastructure development through shared energy resources (Sebitosi and Okou, 2010). However, lack of investment is the major challenge faced by the grouping. The other challenge of the SAPP is that the decentralisation of energy generation is mostly dependent on the regional powerhouse, South Africa (Schreiner and Baleta, 2015).

Demand for energy in the region continues to increase due to population, industrial growth, and urbanisation, creating power shortages that have caused power blackouts currently experienced in the region. Current electricity generation fails to meet local demands (Table 2.2), as evidenced by load shedding in several member states.

Table 2.2: Energy deficits in some SAPP member countries

Country	Installed capacity (MW)	Net capacity (MW)	Maximum demand (MW)
Angola	2210	1805	1599
Botswana	892	460	610
DR Congo	2442	1485	1381
Lesotho	72	72	150
Malawi	351	351	326
Mozambique	2308	2279	830
Namibia	501	392	629
South Africa	46963	41074	36170
Swaziland	70.6	70	221
Tanzania	1380	1143	935
Zambia	2128	2029	1987
Zimbabwe	2045	1600	1671
Total	**61362.6**	**52760**	**46509**

Source: SARDC (2016)

For example, the average outage of electricity in 2008-2009 was 6.70 hours, corresponding losses of 5.4% of annual sales (Mandelli *et al.*, 2014). This inadvertently threatens the success of the region's industrialisation and job creation goals. Table 2.2 shows that some regional countries' present electricity generation capacity hardly meets local demand (SARDC, 2016). According to the Southern Africa Regional Infrastructure Development Master Plan (RIDMP) of 2012, assuming an average economic growth rate of 8% per annum, energy demand is expected to increase to more than 77 000 MW by 2020 and to over 115 000 MW by 2030, exerting more pressure on water resources (SADC, 2012).

2.3.3 Food security in southern Africa

Agriculture is the main catalyst for economic development in southern Africa as more than 60% of inhabitants depend on it for their livelihoods, providing their subsistence, employment and income. The performance of the agriculture sector, therefore, significantly impacts economic growth, poverty reduction and food security as the sector accounts for close to 17% of the region's gross domestic product (GDP), and the contribution increases to over 28% when middle-income countries are excluded (SADC, 2014). Despite its importance to regional economic growth, agricultural growth rates remain very low and highly variable, averaging only 2.6% per annum (Figure 2.6), falling way below the regional target of 7% per annum. Agriculture growth rates have almost been at par with population growth rates of 2.4% (Chilonda and Minde, 2007), resulting in challenges of food insecurity. Thus, the current annual performance of the sector has been insufficient to significantly contribute to regional economic growth and address food and nutrition security issues in the region.

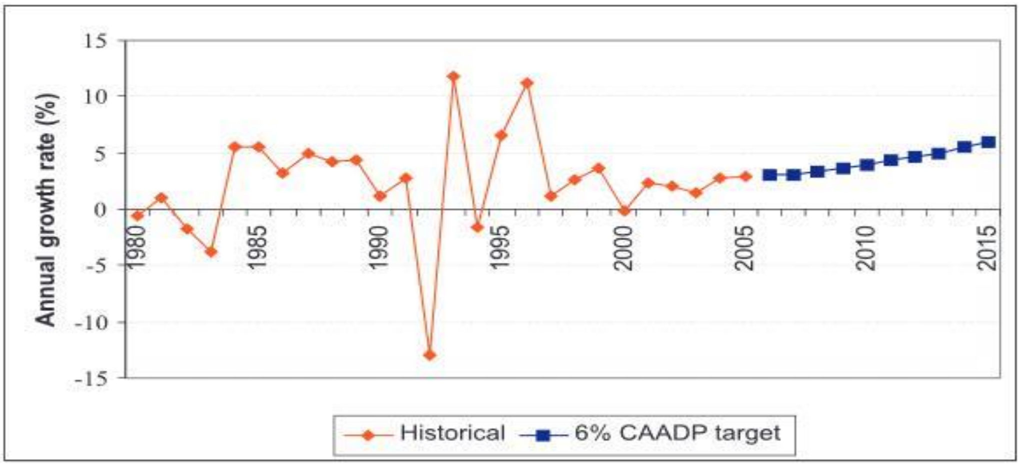

Figure 2.6: Variability in agricultural growth rates in the SADC region.
Source: Chilonda and Minde (2007)

Agriculture is mainly rainfed, and land with irrigation potential is approximately 20 million ha, of which only 3.9 million ha is equipped for irrigation, accounting for about 6.6% of cultivated area (SADC, 2016a). The region is characterised by extreme weather events of drought and floods, causing water, energy and food insecurity. An example is the 2015/16 drought which caused over 40 million people to be food insecure, as dam water levels were reduced, causing intermittent power outages in most countries (SADC, 2016b).

The poor performance of the agriculture sector is mainly due to insufficient investment, poor access to agricultural inputs and markets, poor agronomic practices, low levels of technological development in agriculture, reliance on rainfed agriculture and extreme weather events (Nhamo *et al.*, 2016). For example, the production of maize, the staple food crop consumed in the region, has been decreasing in most regional countries due to a combination of these factors. Table 2.3 indicates the deficits in maize production in most regional countries since 2011, except for Zambia, which shows minimal surplus (FAO, 2016).

Table 2.3: 2016 maize production deficit in southern African countries and the number of affected people

Country	2011-15 average (000 tons)	2015 maize production (000 tons)	2016 maize production (000 tons)	% change 2015/2014	No. of affected people in 2016
Angola	1 366	1 878	1 500	-20	756 000
Botswana	21	4	1	-75	1 100 000
Lesotho	74	79	25	-68	709 000
Madagascar	393	350	300	-14	1 400 000
Malawi	3 583	2 776	2 369	-15	6 500 000
Mozambique	1 602	1 357	1 350	-1	2 000 000
Namibia	61	38	46	21	729 000
South Africa	12 345	10 629	7 733	-27	14 300 000
Swaziland	89	82	33	-60	638 000
Zambia	2 894	2 618	2 873	10	976 000
Zimbabwe	1 083	742	512	-31	4 000 000

Source: GIEWS (FAO, 2016)

These factors, coupled with the underutilisation of arable land where only 21% of the region's 225.6 million ha of arable land is under cultivation and 3.5% under irrigation (Nhamo, 2015), further increase the vulnerability of the region to climate change and food insecurity. The situation could worsen soon with the anticipated population growth if agriculture production does not improve (Alexandratos and Bruinsma, 2012).

The region's plans for increasing agricultural productivity are underpinned by increasing the land area under cultivation and irrigation. This alludes to land use changes in some cases and increasing the number of water withdrawals, and associated energy outlays needed for irrigation. Proponents argue that this is feasible given the region's large tracts of underutilised arable land and water resources (dams). On the other hand, there is an argument that much of the land is degraded and may not be suitable for agriculture and that in some countries, such as South Africa, most of the available water is already allocated and with little scope for building new dams. From a strategic perspective, climate models estimate decreases of about 20% in annual rainfall by 2080 in southern Africa (Conway *et al.*, 2015); this challenges the sustainability of irrigation expansion in a water-scarce future. Either way, adopting a

WEF nexus approach offers opportunities for coordinated planning to increase efficiencies and develop a WEF nexus-sensitive agricultural plan.

Southern Africa has adopted a Programme of Action covering cooperation in various sectors, including food security and natural resources management. To enhance food security throughput in the region, a Food Security Sector was established in 1980. The Food, Agriculture and Natural Resources (FANR) provide the Secretariat for this programme. The main objective of the FANR is to ensure food security and management of natural resources and attain food self-sufficiency.

2.4 Climate change and the WEF nexus

Climate change projections for the southern Africa region show that the greatest impacts will mostly be felt through water resources, which could severely affect food and energy production (Schultze, 2012). Climate models estimate decreases of about 20% in annual rainfall by 2080 in southern Africa, which could cause a reduction in water available for energy generation and crop production (Conway *et al.*, 2015). The situation is worsened by population and industrial growth (Mekonnen and Hoekstra, 2016; Naik, 2017). These already evident stressors are negatively impacting energy generation and supply, as well as food and water security, affecting the development targets of the region (SARDC, 2016). Thus, the WEF nexus presents an opportunity for coordinated resource management for sustainable development, promotion of regional cooperation, ensuring regional security and mitigating regional vulnerabilities.

Climate change is also causing extreme changes in plant habitat distribution, impacting the region's cropping and food security (Park *et al.*, 2015). This is mostly due to decreasing rainfall totals, increased rainfall variability and frequency and intensity of drought and flooding, and increasing temperatures. This is causing shifts in seasons, reduction in season length/duration and shifting agroecological boundaries. The declining rainfall and increasing temperatures worsen the region's vulnerability to the impacts of climate change. The region is now marked by great spatio-temporal climate and water resource variability, particularly in the southern drier countries (Figure 2.7).

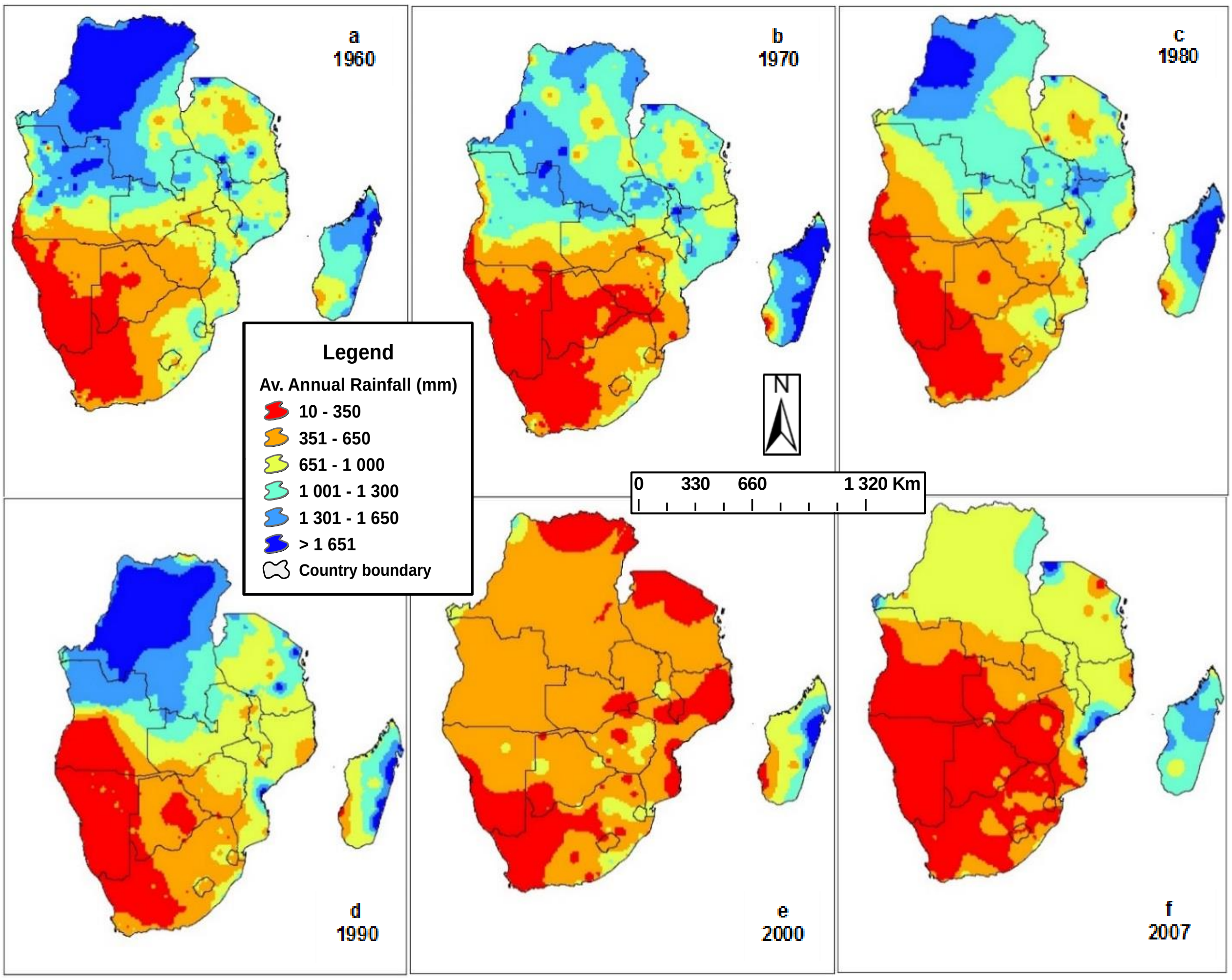

Figure 2.7: Spatio-temporal changes in rainfall distribution in the SADC region over time Source: Nhamo et al. (2018).

As water is key to the WEF nexus, the decrease in rainfall consequently impacts energy generation and food production, compromising regional security (Conway *et al.*, 2015). The spatio-temporal changes in the distribution of annual rainfall in southern Africa are indicated in Figure 2.7 as a, b. c, d, e & f for 1960, 1970, 1980, 1990, 2000 and 2007, respectively. The spatio-temporal maps of rainfall for the mentioned years indicate significant changes that occurred in the region during the 47 years. Total annual rainfall declined to unprecedented levels, from 1 500 to 890 mm between 1960 and 2007. Almost half of the region has become arid, receiving less than 650 mm of rainfall (Figure 2.7f). Generally, the region is marked by great spatio-temporal climate and water resource variability. The decreasing rainfall over the years signifies an increasingly drying region needing better water resources management.

The recurrence in the intensity and frequency of droughts and floods is worsening the region's vulnerability, threatening to reverse economic gains made in the past (SADC, 2016b). Transboundary water resources present an opportunity for regional cooperation in resource management, promoting climate change resilience, and mitigating vulnerabilities. For example, the impact of the 2015/16 El Niño Southern Oscillation (ENSO) drought affected all regional countries causing more than 40 million people (14% of the SADC population) to be food insecure (SADC, 2016b). Dam water levels declined, and crop yields reduced, causing energy and food insecurity (de Waal and Vogel, 2016; SADC, 2016b; Gizaw and Gan, 2017). Also, water levels in Lake Kariba (shared between Zambia and Zimbabwe) were reduced to 12% of capacity in February 2016 compared to the 53% recorded at the same time in 2015 during the drought period (Muchuru *et al.*, 2016). As a result, potential annual power generation is reduced by more than 50%. Similarly, in October 2015, Tanzania was forced to switch off all its hydropower plants due to low dam water levels (SADC, 2016b), causing a decline of 20% in hydro-power generation. Tanzania has since converted some of its hydroelectricity plants to natural gas (SADC, 2016b). At the southern Africa level, available operating capacity in 2016 stood at 46 910MW against a demand of 55 093MW (SADC, 2016b). The 2015/16 drought was so severe that it caused 643 000 livestock deaths and an overall maize (the staple crop) deficit of 5.1 million tonnes, which is a 10% decrease in production compared to the previous year and a 15% drop compared to the 5-year average (SADC, 2016b). Consequently, the region had to declare a drought emergency and launched a US$2.7 billion drought relief appeal to the international community (SADC, 2016b).

One example of the most important benefits of the WEF nexus in regional cooperation and integration is the interbasin water transfers for the benefit of water-scarce countries. Figure 2.8 illustrates the region's current and planned interbasin transfers (Turton, 2016).

Figure 2.8: Current and planned transboundary interbasin transfers. Source: (Turton, 2016). Note: Red lines indicate current transfers; purple lines indicate planned

The most significant of these transfers is between Lesotho and South Africa. The Lesotho Highlands Water Project (LHWP) aims to address South Africa's water scarcity through the transfer of some of Lesotho's abundant water resources to the Gauteng region. The revenues from this project are enabling Lesotho to develop its hydropower capacity and improve water distribution within the country (WorldBank, 2016). There needs to be scope to build on such transboundary transfers to address water scarcity in countries such as Botswana.

2.5 WEF nexus-related institutions and policies in southern Africa

The shared water resources through the region's large transboundary river basins and well-documented history of electricity trade in member states create opportunities for a strong regional dimension to address national water, energy and food security priorities. Because of the shared resources and common climatic, cultural and political history, the region has put in place institutions, policies and other frameworks to oversee and direct water, energy and agriculture resources at the regional level. However, there is a lack of coordination among the policies and institutions, often resulting in policy spill-overs (Kling *et al.*, 2017) and wasteful duplication. Harmonising regional policies for an integrated approach to resource management for sustainability is necessary.

Figure 2.9: Nexus policies need to talk to each other.

The SADC Treaty is the overarching framework for the region, whose objective is to achieve economic development, peace and security, growth, alleviate poverty and improve the people's livelihoods; all these are achieved through regional integration (SADC, 2011). Since the establishment of the SADC, regional integration has slowly increased, including in the water, energy and agriculture sectors. This integration has occurred despite the need to enhance institutional and human capacity to design, prepare, sequence, coordinate implementation, and monitor regional operations. The SADC treaty provides that member states should develop a set of legal and institutional instruments (referred to as protocols) that have clearly stated objectives, scope, and institutional mechanisms to facilitate cooperation and integration on key issues for the region. The region currently has 26 protocols, including the Revised Protocol on Shared Watercourses and the Protocol on Energy. These documents provide the region with a foundation for regional cooperation and integration in water, energy and agriculture.

To date, the region has ratified the following nexus-related policies (Table 2.4) and institutions (Table 2.5):

1. The Regional Strategic Action Plan IV (RSAP IV) (SADC, 2016a) is based on the SADC Water Policy and Strategy that aims to achieve an equitable and sustainable utilization of water for social and environmental justice, regional integration and economic benefit for present and future generations. The RSAP IV emphasizes the importance of infrastructure development and water resource management for food security in the water-food nexus and the stronger urgency to take action regarding climate variability and change.
2. The SADC Protocol on Shared Watercourses (SADC, 2000) fosters closer cooperation for judicious, sustainable, and coordinated management, protection and utilization of shared watercourses. It advances SADC's agenda of regional integration and poverty alleviation. As a result, most shared river basins have basin-level agreements that oversee the day-to-day management of the basins with assistance from the SADC Water Division. Current shared river basin agreements include the Limpopo Watercourse Commission (LIMCOM), Okavango River Basin Commission (OKACOM), Orange-Senqu River Commission (ORASECOM) and Zambezi River Basin Commission (ZAMCOM). The watercourse protocol (Figure 2.10) illustrates the institutional framework for its implementation at both regional and national levels.
3. The Southern African Power Pool (SAPP) is a grouping that was established in 1995 and guided by the SADC Protocol on Energy (SADC, 1996), which highlights the development and updating of a regional electricity master plan, the development and utilization of electricity in an environmentally sound manner, and emphasising the need for universal access to affordable and quality services. The mandate of the SAPP is to enhance regional cooperation in power development and trade and to provide non-binding regional master plans to guide electricity generation and transmission infrastructure delivery. A Regional Energy Access Strategic Action Plan (REASAP) was approved in 2011, setting broad goals for improving access to modern forms of energy as well as specific policy mechanisms to achieve increased access. However, no Regional Strategic Action Plan for Energy has been officially adopted. A

Renewable Energy Strategy and Action Plan (RESAP) was approved in 2016, and a SADC Centre for Renewable Energy and Energy Efficiency (SACREEE) was established in Namibia.

4. The SADC Regional Agricultural Policy (RAP) (SADC, 2014) envisages integrated water resource management approaches. It emphasises the importance of improving agriculture performance to meet food and water security and attain sustainable economic development objectives at the regional level. The RAP oversees the upgrading and expanding water infrastructure for agriculture, data collection for dams, irrigated areas and irrigation management. The SADC's Regional Indicative Strategic Development Plan (RISDP) (SADC, 2003) is derived from the Africa-wide Comprehensive Africa Agricultural Development Programme (CAADP) that promotes the doubling of irrigated areas from 3.5% to 7% by 2025. The CAADP (CAADP, 2009) provides a common framework for stimulating and guiding national, regional, and continental initiatives on enhanced agricultural productivity and food security.

Table 2.4: WEF nexus-related policies

Water	Energy	Food (Agriculture)
• The SADC Revised Protocol on Shared Watercourses (2000) • Regional Water Policy (2005) • A 5-year Regional Water Programme: Regional Strategic Action Plan (RSAP) • RSAP IV (2016-2020) consists of 8 programmes, out of which is a Water, Energy, and Food (WEF) security nexus • Climate Change Adaptation in SADC: a Strategy for the Water Sector	• The Protocol on Energy (1996) and the SADC Energy Cooperation Policy and Strategy (1996) • SADC Energy Action Plan (1997)/SADC Energy Activity Plan (2000) • Regional Energy Access Strategic Action Plan (REASAP) (2011, WEF related • Regional Strategic Action Plan for Energy (2012)? • Renewable Energy Strategy and Action Plan (RESAP) (2016)	• Regional Agricultural Policy (RAP) (2014) • Regional Agricultural Investment Plan (2017-2022-draft) • SADC Food and Nutrition Strategy (2015-2025) (2014) • Agricultural Development Fund (ADF)-2017 • SADC Dar-es-Salaam Declaration on Agriculture and Food Security (2004

Table 2.5: WEF nexus-related institutions

Sector	Regional Structures	Objectives/mandates
Food, Agriculture, Natural Resources	Food, Agriculture and Natural Resources (FANR)	▪ Development, coordination and harmonisation of agricultural policies and programmes
Water and Energy	Infrastructure and Services Directorate	▪ Development, coordination and harmonization of Energy, Transport and Communications, Tourism and Water policies, strategies, programmes and projects; ▪ Coordination and promotion of integrated management of transboundary water, tourism, transport and communication and energy resources for regional integration and development;
	Water Division SADC-RBOs	▪ To oversee the harmonisation of national water use policies and moderate transboundary issues.
	▪ SADC Centre for Renewable Energy and Energy Efficiency (SACREEE) ▪ Southern African Power Pool (SAPP) ▪ Regional Electricity Regulatory Association.	

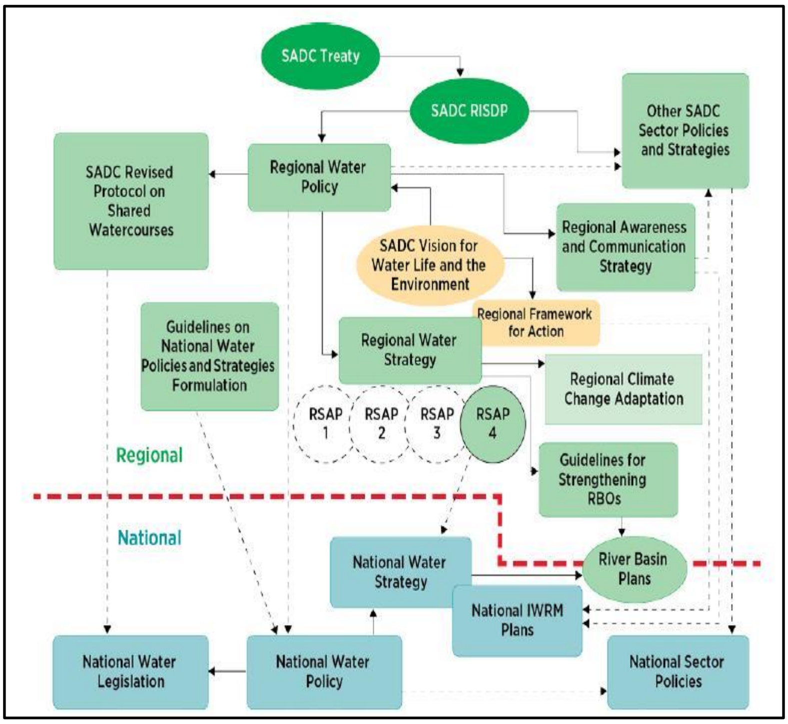

Figure 2.10: SADC water sector legislation, policies and strategies.

Source: (SADC, 2016a)

2.5.1 SADC WEF nexus initiatives

The region produced the WEF Nexus Action Plan, which is incorporated in the RSAP IV, in recognition of the importance of the nexus in regional socio-economic security and cooperation and integration, as well as due to the need to respond to the recurrence of drought in the region (SADC, 2016a). The WEF Nexus Action Plan (Figure 2.11) aims to create an enabling environment for accelerated industrial growth and pilot the nexus to facilitate a better understanding of the nexus benefits.

The action plan recognises the role of the nexus in adapting to the challenges posed by population growth and climate change and variability, as well as in optimising resource use to achieve regional goals and targets. The plan calls for a regional nexus assessment study to provide policy recommendations and strategic actions informed by research and scientific evidence. Key activities include mobilising resources for a regional nexus study in collaboration with other sectors and identifying and implementing regional nexus demonstration projects and studies.

Despite the nexus action plan, there is little or no evidence of cross-sectoral linkages in institutions, policies and current projects. Some activities in recognition of the importance of the nexus include the 2013 SADC multi-stakeholders water dialogue that focused on exploring nexus opportunities in providing coherent and well-planned development and use of resources. A follow-up multi-stakeholders water dialogue will be held in 2017 in Madagascar, focusing on regional value chains and job creation through the WEF nexus. While these efforts are commendable, there is a need to develop action plans with clear timelines on how the WEF nexus should be adopted and implemented.

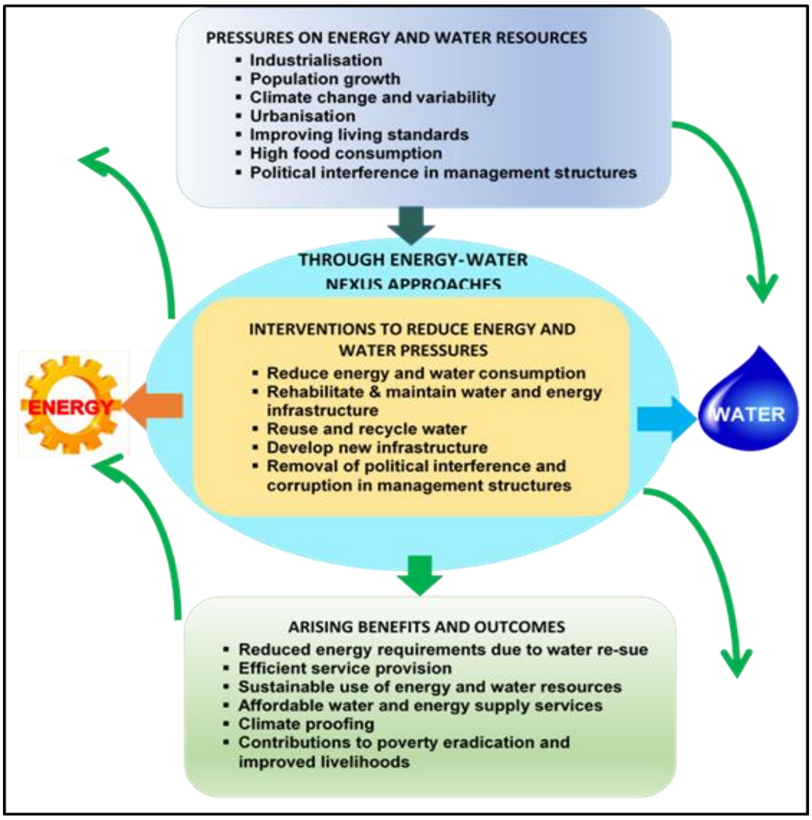

Figure 2.11: Energy-Water Action Plan conceptual framework. Source: (WorldBank, 2016)

2.5.2 WEF infrastructure development and investment

There is considerable potential for coordinated infrastructure investment to improve the overall use of WEF nexus resources in southern Africa. Currently, only 14% of the region's actual renewable water resources (ARWRs) are stored, 8% of its hydropower potential is realised, and 6.6% of cultivated land is equipped for irrigation (WorldBank, 2016). The Regional Infrastructure Development Master Plan (RIDMP) (SADC, 2012) sets out the region's infrastructure development. The RIDMP is structured around a series of targets, which include developing storage for 25% of ARWRs (eventually to reach 75%), increasing installed hydropower generation capacity from 12 GW to 75 GW (50% of potential) (SADC, 2012) and increasing investment in irrigation and land under irrigation by 7%.

The RIDMP has ambitious goals staggered into three phases of investments with a total budget of $200 billion (the total cost includes studies, facilitation projects, and capacity-building projects). Implementation of Phase 1 is currently underway to deliver 34 projects, between 2013 and 2021 (Table 2.6), with an estimated total project cost of $16 billion (SADC, 2012). However, the planned projects show little regional integration. Of the 34 identified Phase 1 investment projects, only four are between two countries, and 1 (irrigation efficiency project) stretches across the entire region. There are no projects between three or more countries (Table 2.6) (Schreiner and Baleta, 2015; WorldBank, 2016).

Table 2.6: SADC RIDMP water plan investment projects

Project	Lead agency	Cost (millions of US$)
Inga III hydropower	Ministry of Energy, DRC	8,000
Lesotho Highlands – Phase 1	LHDA and LHWC, Lesotho	1,001
Batoka Gorge hydropower scheme	ZRA/ZESA/ZESCO	4,000
Songwe River Basin development project	Malawi and Tanzania	328
Vaal-Garnagara water supply	DWA Botswana	175
Ressano Garcia Weir	DNA Mozambique	6
Lomahasha/Namaacha water supply	Mozambique and Swaziland	31
Water supply and sanitation at 12 locations	Zambia	165
Water supply and sanitation – Lubango Phase 2	Angola	120
Water supply and sanitation – Kinshasa	Ministry of Energy DRC	220
Lesotho lowlands water supply scheme – Zone 1	LHWC Lesotho	78
Mombezi multipurpose dam	Blantyre Water Board	210
Water supply and sanitation – 13 housing estates	Mauritius	11
Movene Dam	DNA Mozambique	11
Artificial recharge of Windhoek aquifer – Phases 2B & 3	NamWater	55
Reducing non-revenue water & increasing use efficiency	Seychelles	26
Nondvo multipurpose dam	DWA Swaziland	150
Ruhuhu Valley irrigation scheme	Tanzania	13
Climate change adaptation to drought – agro region 1	Zambia	80
Bulawayo-Zambezi water supply scheme	Zimbabwe	600
Improved agricultural water application efficiencies	SADC Water Division	11.5

Source: SADC (2012) and WorldBank (2016)

The international community has committed to finance regional WEF projects through the World Bank. Table 2.7 shows the amount allocated to regional projects in 2015 (WorldBank, 2015).

Table 2.7: Funding of nexus-related projects

Basin/REC/Sub-Program/Activity	Description	Allocated Amount (US$)
Zambezi	Zambezi River Basin Management (ZAMCOM), ZRB Development (ZRA), Zambezi Support Program	13,400,000
Okavango	Okavango Multi-Sector Investment Analysis	900,000
Orange-Senqu	Lesotho Highlands-Botswana Water Transfer Study	2,175,000
SADC	SADC Groundwater Management	2,300,000

Source: WorldBank (2015)

There are also energy generation and grid connection projects in the energy sector, with an estimated cost of between US$290,000,000 and US$420,000,000. Table 2.8 shows the energy projects currently underway in the region.

Table 2.8: SADC energy projects

Name of Project	Cost estimate (US$ million)	Member States	Estimated Completion Year
Mpanda Nkuwa Hydro Power Station – Phase 1	2,000.00	Mozambique	2016
ZIZABONA Interconnector Project	223.00	Botswana, Namibia, Zambia and Zimbabwe	2015
Zambia-Tanzania-Kenya (ZTK) Power Interconnector Project	860.00	Zambia, Tanzania, Kenya	2016
Namibia-Angola Interconnector	250.00	Namibia, Angola	2016
DRC-Angola Interconnector	95.00	DRC and Angola	2016
Mozambique-Malawi Interconnector	93.00	Mozambique, Malawi	2016
2nd SA-Zimbabwe Interconnector	280.00	SA and Zimbabwe	2017
2nd DRC-Zambia Interconnector	80.00	DRC and Zambia	2017
Mozambique Backbone Project	1,700.00	Mozambique	2020

Name of Project	Cost estimate (US$ million)	Member States	Estimated Completion Year
Cahora Bassa North Bank Power Station	800.00	Mozambique	2017
Inga III Hydro Power Project	1,730.00	DRC	2018
Central Transmission Corridor Network (CTC) Phase II	100 .00	Zimbabwe	2016

Further, Table 2.9 and Figure 2.12 present some regional WEF-related targets. The WEF nexus approach to resource management provides a balanced resource allocation for sustainability.

Table 2.9: SADC WEF-related targets

Project	Potential	Baseline (2012)	Targeted Plan (2027)
Hydropower	150 GW	12 GW	Increase to 75 GW (50% of potential)
Irrigation	50 M has	3.4 M has	Increase to 10 M has (13% of potential)
Renewable WR	2,300 km^3	14% retained	Increase to 25%
Access to clean water		61%	Increase to 75%
Access to sanitation		39%	Increase to 75%

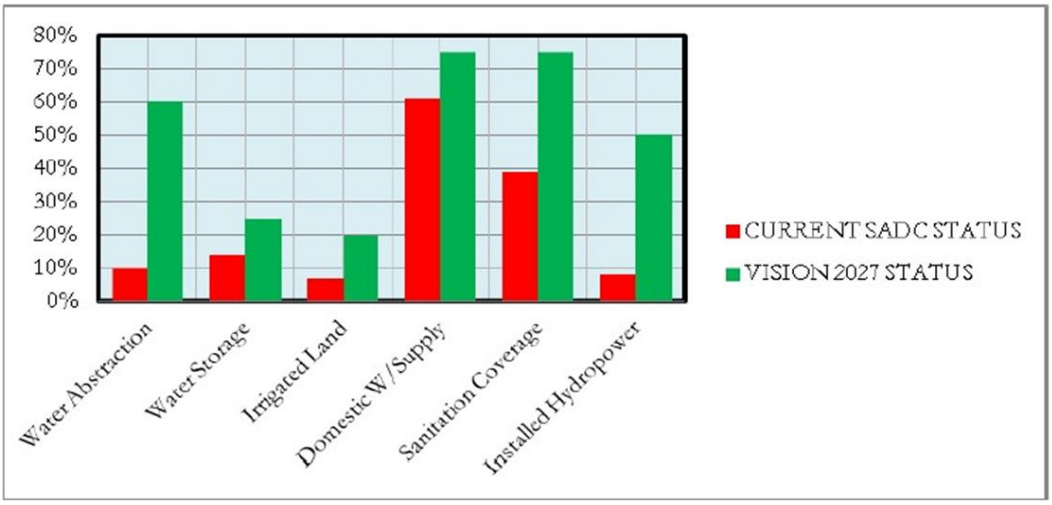

Figure 2.12: SADC WEF integrated plans and programs for resource-use efficiency.

Sources: (SADC, 2012)

2.5.3 Major challenges in implementing the WEF nexus

The review of SADC policies and WEF institutions highlights that there is a sound foundation for adopting a WEF Nexus approach. However, challenges still exist in achieving this. Current evidence suggests that despite the documented institutional and policy arrangements, there is no tangible action on the ground. This is because the focus tends to be mainly at country or basin levels. Individual member states' priorities are more informed by sovereignty and attaining water, energy and food security at the country level. This sentiment on political sovereignty, driven by the region's colonial past, remains strong at the national level. This inadvertently tends to scupper regional integration efforts as member states will prioritise national projects in funding.

Additionally, genuine integration is limited by regional policy sections that allow member states to retain the right to develop and implement their national plans; regional master plans are not necessarily binding on individual member states. In this regard, there needs to be a paradigm shift among member states regarding the governance of water, energy and food/land resources, as well as the concepts of water, energy and food security. Such a paradigm shift requires a shift from nationally driven to regionally driven. As has already been highlighted, the transboundary nature of resources could ensure regional water, energy and food security. This paradigm shift is, however, challenged by a chronic lack of infrastructure to support such integration and transfers. Thus, another major challenge to implementing the WEF nexus in southern Africa is the lack of infrastructure.

Another challenge is that there are few case studies for implementing the WEF nexus, meaning there is limited evidence to support its adoption. While the plan is always to increase, this often overlooks the need to improve current efficiencies. To address current deficits, there is a need to optimise the current water, energy and food production resources in a coordinated manner. This could serve as a regional base for implementing the WEF nexus approach and help canvass its adoption. Existing regional policies and strategies promote action research to develop and sustainably implement resilient water-related infrastructure and develop innovative technologies to direct practice. This agenda is challenged by a lack of funding for WEF-related projects that can demonstrate this action research to generate financial resources for case studies. For example, the adoption of regional policies by member states such as Malawi, Zambia, Zimbabwe and Mozambique over the past decade has translated to increased budgetary spending on agriculture towards the regional target (10%); however, lack of investment in agricultural water management remains low (SADC, 2014).

A third challenge to implementing the WEF nexus is the region's socio-economic challenges. The recurrence of natural hazards such as droughts and floods has also placed pressure on the region's socio-economic challenges and how individual member states prioritise WEF-related sectors' development. For example, the recurrence of droughts has shifted regional efforts and priorities towards increasing irrigation and land under irrigation, often with minimal consideration for WEF nexus synergies and trade-offs. This also contributes to the slow implementation of the WEF nexus. Furthermore, high levels of poverty, unemployment, and political instability in some parts of the region present a challenge to implementing the nexus and integration. Also, opening up may trigger economic and political and economic migration. It is important to note that while this remains a challenge, it also provides an opportunity to showcase how implementing the WEF nexus can translate to job creation and general improvement in the quality of life for southern African citizens. The following section details other challenges related to monitoring and evaluating the WEF nexus.

2.6 Implementation and monitoring of the WEF nexus

Following the previous section, another conundrum relates to monitoring and evaluating the WEF nexus. Although the importance of the WEF nexus is now recognised, its implementation, monitoring and evaluation are challenged by a lack of integrated WEF nexus indicators and indices for quantifying the nexus (Rees, 2013; Leck *et al.*, 2015). The lack of indices and/or metrics and models for assessing the WEF nexus renders its adoption rhetoric. The basis of the nexus approach is an attempt to balance different uses of ecosystem resources (energy, water, land, soil and socio-economic factors). The current sectoral approach to their management means that mechanisms for monitoring, evaluating and assessment are sector-specific, with different sectors using different indicators; the lack of WEF guidelines and evidence-based case studies (Section 2.5.3) has inadvertently contributed to the status quo (WEF, 2011).

To successfully implement, monitor and assess the WEF nexus, there needs to be WEF nexus-specific targets and indicators that highlight and quantify the linkages, synergies and trade-offs. Due to the prevailing sectoral approaches, a wealth of sector-specific models and tools have successfully been applied to monitor sector targets and indicators (Table 2.3). The remaining challenge would be linking these sectoral indicators, indices and models to provide an evidence-based framework for assessing the WEF nexus. Therefore, a starting point would be to explore existing indicators, metrics and indices available from regional WEF sector statistics to identify “nexus points”, with those metrics that show existing nexus points being proposed. Since the WEF nexus is essentially an attempt to balance different uses of ecosystem resources and transfer such benefits to human well-being (Miralles-Wilhelm, 2016), these models could be either biophysical or economic.

The WEF nexus could lead to a more optimal resource allocation to promote inclusive and sustainable regional economic growth (Bizikova *et al.*, 2014). However, this will depend on the availability of support from harmonised WEF institutions, policies, and evidence-based targets and indicators.

2.6.1 Integrated WEF nexus assessment models

There are currently ongoing efforts to develop models for assessing WEF nexus relationships. For example, Figure 2.13 illustrates the integrated nexus assessment models proposed by (Kling *et al.*, 2017).

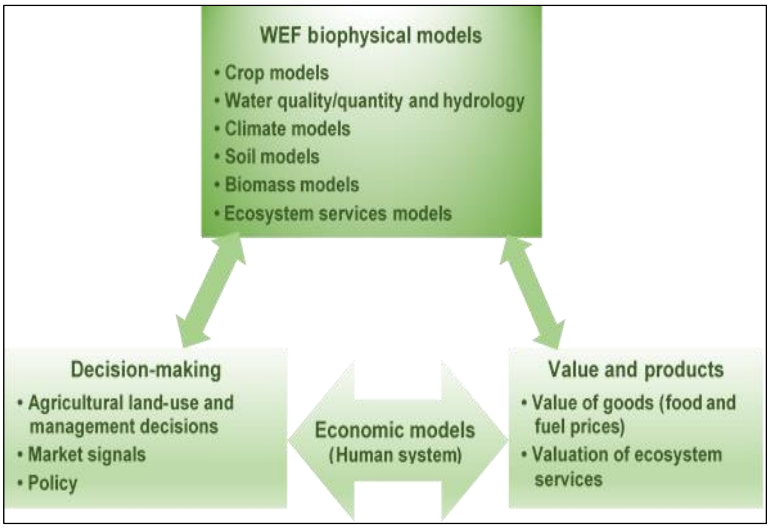

Figure 2.13: Integrated WEF nexus assessment models.

Adapted from (Kling *et al.*, 2017)

Their proposed model indicates the relationship between natural systems and human decisions, policies, and values (Section 2.5.3). The model showcases the interface between the human system or economic models (policies and institutions) and the biophysical systems. The economic or human system is divided into two separate but interrelated categories, i.e. decision-making and the value of ecosystem goods and services as they are transformed for human well-being (Kling *et al.*, 2017). Each system has a representative component(s) from which models can be derived to evaluate the WEF nexus. The models are central to developing and evaluating goals and indicators for the WEF nexus. (Kling *et al.*, 2017) the model emphasises the significance of an integrated nexus approach for achieving human well-being and sustainable development. This is supportive of regional goals and the linking of the WEF nexus to the Sustainable Development Agenda.

The underlying premise should be that within a WEF nexus-sensitive governance, decision-making should be supported by integrated analytical tools or assessment models. There remains a major gap in knowledge on developing such models and tools. Similar to the issue of indicators, a starting point could be an assessment of existing tools and models that are being used in the WEF sectors. In this regard, Table 2.10 provides examples of some models and tools that could be considered in developing an integrated WEF nexus assessment model. Geographic Information System (GIS) could also be applied for upscaling and highlighting the spatial distribution of water, energy and food resources.

Table 2.10: Practical models and tools for WEF nexus assessment

Model categories	Model types	Spatial analysis
Crop models	▪ Decision Support System for Agro-technology Transfer (DSSAT) ▪ Agricultural Production Systems Simulator (APSIM)	Geographic Information Systems (GIS)
Economic models	▪ Lagrangian stochastic model ▪ Water Energy Food Nexus Rapid Appraisal Tool ▪ Foreseer Tool ▪ Markal tool	
Energy models	▪ Long-range Energy Alternatives Planning system (LEAP) ▪ IRENA's Preliminary Nexus Assessment Tool	
Water models	▪ Water Evaluation and Planning system (WEAP) ▪ Soil and Water Assessment Tool (SWAT) ▪ Spatially Referenced Regressions on Watershed attributes model (SPARROW)	

2.6.2 Benefits of the WEF nexus to southern Africa

The primary goal for southern Africa is to foster regional growth and integration. This is premised on the realisation that a common history unifies the southern African region, culture and shared natural resources (***cf.*** Section 2.2.4). The entire region faces similar goals related to poverty alleviation, improving the quality of life for its inhabitants, economic development and job creation. It also faces similar challenges, such as increasing population, rural-urban migration, food insecurity, unemployment and inequality. Water, energy and food are central to the region's sustainable economic development and transformation plans. In this regard, the WEF nexus offers significant opportunities for a coordinated approach to addressing some of the region's pressing challenges and achieving regional goals. The following specific benefits could be realised through the adoption of a WEF nexus approach:

- Regional integration. Section 2.2.4 provided detailed context on the extent of southern Africa's shared WEF resources, which transcend political boundaries and sovereignty. Agroecological zones also transcend political boundaries and sovereignty. The WEF nexus provides a meaningful platform for coordinated access, utilisation and beneficiation of these resources and the potential for effective synergies and trade-offs between the WEF nexus components (Van Houtum, 2005; Pittock *et al.*, 2015). The WEF nexus also allows one to harmonise existing institutions and policies and translate them into coordinated, balanced strategies that contribute towards inclusive development, socio-economic security and regional integration.
- Sustainable economic development. The WEF nexus has become central to regional dialogues on economic development and subsequent monitoring of the SDGs. This is because the nexus promotes the inseparable link between using resources to provide basic and universal rights to food, water and energy security (Biggs *et al.*, 2015). Adopting the WEF nexus in the southern African region is envisaged to benefit sustainable resource use that will promote sustainable and inclusive economic development and job creation and improve people's livelihoods.

- Eradicate poverty and improve human well-being. Owing to historical imbalances, most of southern Africa's population (~60%) is impoverished and resides in rural areas. They still lack access to clean and safe drinking water, sanitation, and energy and face chronic food insecurity due to reliance on rainfed agriculture. Consequently, much of the region's policies have been driven by the need to improve human well-being through improved service delivery. As has been alluded to (***cf.*** Section 2.5.2), human well-being is at the core of the WEF nexus. The WEF nexus, through coordinated and shared resource utilisation, has the potential to improve human livelihoods. For example, of the 2 300 km^3/annum of available renewable freshwater water resources, a meagre 44 km^3 is abstracted, and 14% is stored (Schreiner and Baleta, 2015). The balance of this water, which could be captured and redistributed to drier parts, currently either flows to the ocean or evaporates, i.e. non-beneficial. Implementing a regional WEF nexus plan could unlock these water resources and benefit the drier southernmost countries of the southern Africa region. The WEF nexus could also assist in sustainably utilising the 50 million ha of irrigable land (currently only 7% is irrigated) as well as increasing energy generation through harnessing the hydropower potential (150 GW potential versus. 12 GW actual) (Stiles and Murove, 2015) through utilising the region's underutilised dams (***cf.*** Sections 2.3.1 and 2.3.2). These projects, and others, have to improve water, energy and food security in the region, thus, contributing to improved human well-being.
- Harmonisation of institutions and policies. A lot needs to be done to unlock the potential of the WEF nexus approach to effectively exploit the many interlinked development opportunities in the southern African region. Only recently has the WEF nexus found its place in regional policy formulation, as most existing instruments were developed without adequate consideration for cross-sectoral synergies and trade-offs. The lack of vertical and horizontal linkages between sectoral institutions has created an imbalance and duplication among the sectors in terms of demand and supply. The cross-sectoral efforts have remained static, such as considering water for food or energy for food, disadvantaging other sectors. While the SADC's RAP has contributed to an increase in food production in the region, it has resulted in huge pressure on water and energy resources and

has weakened the sustainability of agriculture. The WEF nexus promotes an integrated approach to resource use, thus promoting cross-sectoral balanced and inclusive development. Harmonising institutions and policies among the three sectors minimise cross-sectoral conflicts, maximises synergies, mitigates trade-offs, reduces implementation costs and achieves policy objectives through a systems approach. Harmonised policies systematically promote mutually reinforcing strategies and instruments and resolve policy conflicts to meet competing resource demands. For example, RISDP allows joint planning and implementation of the WEF nexus to maximise synergies among the WEF sectors. This could lead to improved hydropower development and irrigation expansion in a more coordinated manner for sustainable development.

- Build resilience. Climate change does not recognise political boundaries or sovereignty. Climate variability and change threaten and provide a multiplier effect on existing challenges to the SADC's development agenda. The region has been classified as a climate change hot spot, particularly disconcerting due to its dependence on climate-sensitive agriculture and energy sectors. According to climate change projections, the greatest impact will be on the water (Schultze, 2012). Already increasing frequency and intensity of weather extremes (droughts and floods) has retarded economic growth and set back regional targets. The WEF nexus approach provides an opportunity for increasing regional resilience against climate change impacts and mitigating vulnerabilities through coordinated WEF infrastructure development, improved management of transboundary natural resources, maximising regional comparative advantages for agricultural production and unlocking more resources for climate-proofing through increased efficiencies. Implementing the WEF nexus would promote sustainable development, contributing to resilience.
- Promote investment in infrastructure development. The WEF nexus promotes investment in resource-efficient technologies as innovative policies and institutional support to decouple the intensity of resource use from food production are put in place. Once effective strategies are in place, investment is attracted that would benefit the use of modern technologies that include the production and use of renewable energy through hydropower, solar-powered water pumps for

irrigation, generation of electricity from crop residues, production of biogas from manure, and introduction of trees or perennials on farms to produce wood for on-farm energy purposes among others. A regional WEF nexus approach would lead to infrastructure development in countries that currently lag. For example, while northern parts of southern Africa have abundant water resources, they face economic water scarcity due to a lack of infrastructure for storage and distribution. A regional WEF nexus approach could lead to investment in dam construction, hydropower and water distribution infrastructure. For example, the Lesotho Highlands Water Project has boosted infrastructure development and provided employment, hydropower and revenue in Lesotho whilst addressing South Africa's water scarcity. There is a need to replicate such interbasin transfer projects throughout the region.

2.6.3 The WEF nexus framework for the southern Africa region

Figure 2.14 proposed a conceptual framework for a regional WEF nexus. The framework incorporates four idealistic WEF nexus components and their elements (action fields, finance, governance and innovation). In addition, the conceptual framework also takes into consideration the region's transboundary natural resources. Furthermore, the conceptual framework highlights the importance of the WEF nexus in contributing to the SADC's goals related to integration, poverty eradication, improving human well-being and building resilience. The WEF nexus conceptual framework incorporates the following elements described by (Hoff, 2011; Mohtar and Daher, 2016):

1. Strengthening regional policies and governance to manage the WEF nexus and provide political commitment;
2. Cooperation and commitment by member countries in the implementation of the WEF nexus in shared resources for regional socio-economic security and poverty eradication;
3. Promotion of public awareness to cultivate a culture of regional integration and acknowledgement of the role of broader and natural boundaries in regional socio-economic security and improve human well-being; and

4. Provision of evidence-based tools and models to identify synergies, trade-offs, and nexus points and support the development of effective, integrative resource allocation strategies.

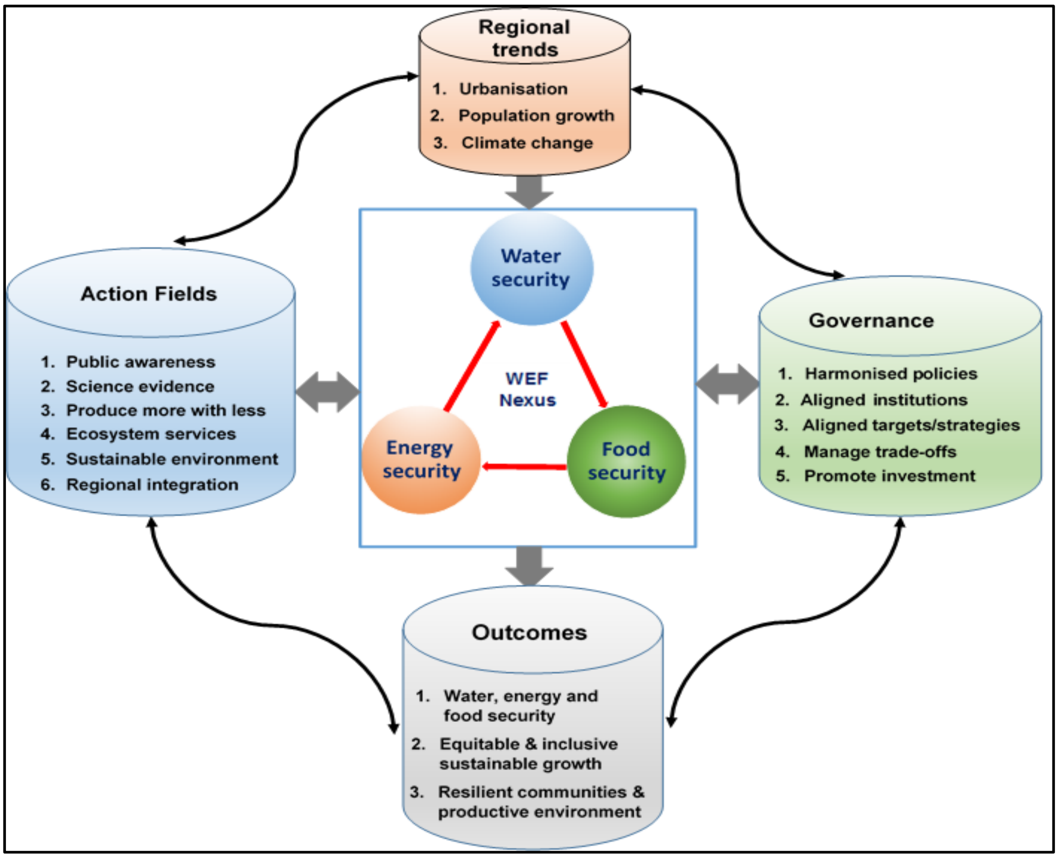

Figure 2.14: Regional WEF nexus framework for the SADC.

Source: (Nhamo *et al.*, 2018)

2.7 Conclusions

Current institutional and governance structures have entrenched a silo effect. This limits the capacity to solve current complex problems requiring cross-sectoral considerations. The southern African region faces water, energy and food insecurity. Climate change projections suggest increased stresses on the WEF sectors, thus challenging future development plans. The WEF nexus approach offers opportunities to effectively achieve sustainable development through cross-sectoral collaboration at a regional level, particularly in southern Africa, where resources are shared. The WEF nexus offers inclusive and transparent intergovernmental approaches for all stakeholders and supports the United Nations' SDGs using scientifically and evidence-based policy, monitoring, assessment and cooperation models. The WEF nexus, thus, offers opportunities to promote peace, regional cooperation and harmonisation of legislations, policies and strategies in a region of transboundary resources. Sectoral policies that are not linked to each other promote unsustainability and unbalanced resource development and growth. The regional conceptual framework and the given model present opportunities for developing a comprehensive analysis approach, identifying synergies and trade-offs in the WEF nexus, and assessing multiple benefits and trade-offs across ecosystem goods and service sectors. Challenges in southern Africa are generally similar among member states as they share the same resources and climate conditions. As the vast and unexploited resources within the region are shared, the WEF nexus presents opportunities for regional integration, coordinated resources development, resilience building and reduction of vulnerabilities, and attainment of regional development targets. However, successfully implementing the nexus at the regional level requires commitment from member states, supported by technological innovations that allow the production of more food with fewer resources. Adopting the WEF nexus approach would be a step towards attaining the SDGs on poverty eradication, zero hunger, availability of water, and access to affordable and reliable energy (goals 1, 2, 6 and 7, respectively). Achieving this requires a paradigm shift from the present sovereignty mindset to one aimed at building integration and strengthening cooperation to break the cycle of instability, extreme poverty and socio-economic insecurities. To effectively implement the WEF nexus, there is still a need to develop a set of indicators for assessing and monitoring WEF nexus resource use.

3 DEVELOPMENT OF iWEF 1.0: A WEB-BASED AND GIS-ENABLED INTEGRATIVE WATER-ENERGY-FOOD NEXUS ANALYTICAL MODELLING TOOL

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3.1 Introduction

Water, energy, food and land are strategic resources that sustain livelihoods and are catalysts for economic development. However, these resources are currently degrading, depleting and stressed due to dynamic changes in environmental (e.g. climate change), technological, economic and demographic conditions (e.g. population growth) (Mabhaudhi *et al.*, 2016; UN-Water, 2018; Yang *et al.*, 2018). Water, energy, and food sector-based policies and management approaches ignore the synergies and trade-offs between water, energy and food resources and further undermine the security of these key resources (IRENA, 2015; Leck *et al.*, 2015). The projections for 2030 and 2050 predict demand increases of 40-50% for water, 50-100% for energy, 50-60% for food, and 20% for agricultural land (WEC, 2013; IRENA, 2015; FAO, 2022; UNESCO, 2022). Previous approaches to integrated resources management were siloed, for example, the water-centric integrated water resources management (IWRM), which led to the pursuit of alternative approaches that are holistic and integrated approaches, specifically the water-energy-food (WEF) nexus approach (Leck *et al.*, 2015; Schull *et al.*, 2020). IWRM treats water as the entry point, which may lead to trade-offs in other linked sectors, thus triggering inefficiencies of WEF resources utilization and compromised resources security (Stucki and Smith, 2011; Benson *et al.*, 2015; de Loë and Patterson, 2017; Grigg, 2019).

As stated at the Bonn 2011 Nexus Conference for WEF Security Nexus Solutions for the Green Economy, wherein the concept gained prominence, the WEF nexus inextricably links water, energy and food resources and sectors at different levels and scales (Figure 3.1) (Hoff, 2011; Flammini *et al.*, 2014; IRENA, 2015). Livelihoods and ecosystem (or environment) health are central elements that depend on the flow of resources between sectors, which are all impacted by demographics, economy, and climate.

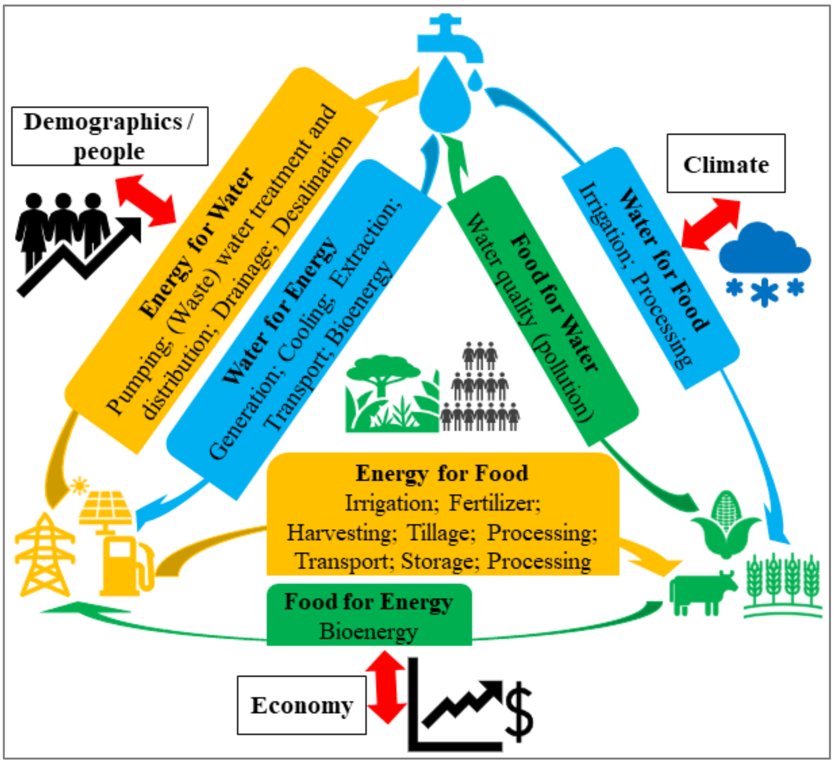

Figure 3.1: A graphic illustration of the WEF nexus

Water contributes to energy generation technologies and processes within the WEF nexus. For instance, in hydropower plants flowing water turns turbines; in thermal and nuclear power, water is used for cooling high temperatures and powering turbines with steam energy. Water is a key input in the production of crops for biofuels. On the other hand, energy is used to extract, convey, treat, and distribute water. Agriculture uses about 70% of the global water in irrigation, food and fibre production (WorldBank, 2020). Untreated food waste and agricultural return flow with nitrates, phosphates and sulphate residues from fertilizers and pesticides pollute surface and groundwater, thus compromising water quality and quantity (FAO, 2014; Wicaksono *et al.*, 2017).

Furthermore, accelerated agricultural intensification and land expansion alter the local hydrology, affecting water availability and quality. When it comes to food, its production consumes either direct or indirect energy. Furthermore, food contributes to energy production by converting agricultural products into bioenergy such as bioethanol, biodiesel and biogas (IRENA, 2015; Wicaksono *et al.*, 2017; Wicaksono and Kang, 2019). These examples testify to the multidimensionality and relative complexity of the WEF nexus concept and approach, whose translation from theory to practice in policy, governance and infrastructure development is still lagging, possibly due to a lack of supporting evidence and tools that can capture it in its entirety (Leck *et al.*, 2015; Liu *et al.*, 2017; AboeInga *et al.*, 2018; Galaitsi *et al.*, 2018; McGrane *et al.*, 2019). Implementing the nexus approach relies on an analysis of cross-sectoral interactions to facilitate integrated planning and decision-making, and this requires the application of quantitative and qualitative decision-support tools and methodologies depending on the motivation of the analysis, access to data and availability of technical capacity (Bazilian *et al.*, 2011; IRENA, 2015).

A WEF nexus modelling tool is an intellectual and mathematical construct of relationships between food, energy, and water systems that simplify and represent reality by capturing the spatial and/or temporal dynamics and feedback between them. WEF nexus models describe a WEF system's structure and function to give insights into select attributes of the system's physical, biological, economic, or social dimensions and dynamics (EPA, 2009; Saundry and Ruddell, 2020). Existing WEF nexus tools include Water-Energy-Food (WEF) Nexus Tool 2.0 (Daher and Mohtar, 2015), Climate-, Land-, Energy- and Water-systems (CLEWs) (Howells *et al.*, 2013), Multiple-Scale Integrated Assessments of Societal Metabolism (MuSIASEM) (Giampietro *et al.*, 2009), and Water Evaluation and Planning System – Long-Range Energy Alternatives Planning System (WEAP-LEAP) (SEI, 2012). In Africa, the Water Research Commission of South Africa (WRC) supported the development of two WEF nexus models, which are the WEF Nexus Index developed by Simpson *et al.* (2022), and the integrative analytical WEF nexus model by (Nhamo *et al.*, 2020a). These and other tools are complex, require extensive input data, are selective of spatial scale and geographic scope, and lack feedback analysis, optimization and visualization (Darghouth, 2005; Flammini *et al.*, 2014; IRENA, 2015; Kaddoura and El Khatib, 2017;

Shinde, 2017; Wicaksono *et al.*, 2017; Dai *et al.*, 2018; Mannan *et al.*, 2018; Shannak *et al.*, 2018; Zhang *et al.*, 2018; Wicaksono and Kang, 2019; Rosales-Asensio *et al.*, 2020).

A recent review of literature by Taguta *et al.* (2022d) discovered that at least 46 WEF nexus tools were developed from 2009 to mid-2021, with a majority unavailable (61%), of unknown format (48%), applicable to large scales (70%), lacking in geospatial analytic capabilities (70%), and being relatively unpopular (61%) in application case studies. 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 or rotten links (Taguta *et al.*, 2022d). 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 and thus limiting their universal applicability (Taguta *et al.*, 2022d). Availability and accessibility are necessary prerequisites for users' wide use of WEF nexus tools for improved nexus-friendly decision-making (IRENA, 2015). WEF nexus tools must be applied locally to tailor appropriate solutions for conditions that leverage synergistic techno-ecological interactions. Preferably, WEF nexus tools should be mandated as multi-scalar, flexible and adaptable across a spatial scale and geographic scope (IRENA, 2015).

Most WEF nexus tools are strong in quantitative and qualitative analysis but weak in spatial analysis, mapping, and visualization. Geographic Information System (GIS) is a computer-based information system with tools to collect, store, manipulate, analyse, and visualize spatially defined data (Johnson, 2009; Janipella *et al.*, 2019). On the other hand, GIS is strong in handling spatial data but weak in integrating decision-making and reasoning preferences into problem-solving (Eldrandaly, 2007). In addition, GIS is an important decision-making spatial tool that can support the precise assessment of distributed WEF resources, thereby addressing economic and environmental goals (Hiloidhari *et al.*, 2017). Thus, GIS and WEF nexus tools are complementary and can be integrated to simultaneously and spatially compute, analyse and map interactions between WEF resources (Eftelioglu *et al.*, 2017).

The lack of geospatial analytic capabilities in WEF nexus tools is a drawback in characterizing the spatial dynamics of the WEF nexus because WEF resources are spatially distributed. Shannak *et al.* (2018) and Ravar *et al.* (2020) echoed the mismatch between the spatial variation of WEF resources and WEF nexus models that spatially aggregate the WEF nexus phenomena leading to deviations from reality in analysis. Thus, WEF nexus modelling tools need to possess geospatial analytic capabilities for spatial characterisation of WEF nexus dynamics which can aid in identifying bright- and hotspots. Integration of WEF nexus tools and GIS is by either soft-linking (Daccache *et al.*, 2014; Kraucunas *et al.*, 2015; Gondhalekar and Ramsauer, 2017; Yuan and Peng, 2017; Basheer *et al.*, 2018; Burger, 2018; Daher *et al.*, 2019; Almulla *et al.*, 2020; Haji *et al.*, 2020; Vinca *et al.*, 2020; Li *et al.*, 2021; Ramirez *et al.*, 2021) or hard-linking (Karnib, 2017; ETHZÜRICH, 2018; Lin *et al.*, 2019; Arenas *et al.*, 2021; Simpson *et al.*, 2022). However, the 'soft-linked' arrangement demands a high level of competence from the user to write data in a shareable format, thus cumbersome and prone to errors (Ramos *et al.*, 2019). On the contrary, the 'hard-linked' integration is superior to the soft-linked arrangement through effective and automatic input and output data exchange between the WEF nexus and GIS components. This beneficial integration utilizes Web GIS, base maps, geodatabases, and geoportals is easier and more convenient for the users. It allows automatic analysis, mapping and visualization (Eldrandaly, 2007). It facilitates flexible web hosting of the tool, locating case study areas, real-time interaction, mapping, visualizing spatial distributions of WEF nexus, as well as spatially quantifying WEF requirements, supply, budgets and footprints (Lin *et al.*, 2019; Arenas *et al.*, 2021).

Although Mabhaudhi *et al.* (2019), Nhamo *et al.* (2020a), and Nhamo *et al.* (2020b) successfully developed the MS Excel-based integrative analytical model for the water-energy-food nexus and applied it at different spatial scales, the tool is unavailable in the public domain. It lacks (i) a user-friendly Graphical User Interface (GUI) and (ii) geospatial analytic capabilities for locating case studies and spatial analysis, mapping and visualization of the WEF nexus. Thus, to address these critical gaps in WEF nexus tools, this study developed and tested a user-friendly web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical modelling tool (iWEF) based on previous work by Mabhaudhi *et al.* (2019), Nhamo *et al.* (2020a) and Nhamo *et al.* (2020b). The iWEF tool is freely available and accessible to interested users; the tool automatically determines the consistency of input data and produces graphs and spatial maps for enhanced quantitative and geospatial analysis and visualization.

3.2 Materials and methods

The iWEF model was developed using model building, programming and web development tools. The tool also integrates a GIS module that facilitates geospatial analytic capabilities by providing quantitative and qualitative spatial information about the WEF nexus from a bird's eye view.

3.2.1 The integrative WEF nexus analytical model (iWEF)

The integrative analytical WEF nexus model was originally developed by Nhamo *et al.* (2020a) as an MS Excel- and Analytic Hierarchy Process (AHP)-based model. The model was designed to establish quantitative relationships among WEF nexus sectors to indicate resource utilisation and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention. In essence, the model holistically evaluates synergies and trade-offs to improve efficiency and productivity in resource use and management for sustainable development (Nhamo *et al.*, 2020a). Nhamo *et al.* (2020a) developed a methodology to compute composite indices based on defined and identified relevant WEF sustainability indicators. These indicators, calculated per annum, include water availability (m^3/capita), water productivity ($/$m^3$), energy accessibility (%), energy productivity (MJ/GDP), food self-sufficiency (%) and cereal productivity (kg/ha). These indicators are compared against each other in a PCM based on expert opinion, literature, or recognized databases (e.g. national statistics, World Bank, Aquastat, etc.) that can provide the baseline to establish the numerical relationship among indicators (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b). These six indicators are defined and explained by Mabhaudhi *et al.* (2019), Nhamo *et al.* (2020a) and Nhamo *et al.* (2020b).

3.2.2 The conceptual model for the iWEF modelling tool

The conceptual model of iWEF (Figure 3.2) is founded on the AHP multi-criteria decision-making (MCDM) framework, which consists of the goal, indicators and pillars. The six indicators are the multiple criteria, and they were elaborated on in Section 3.2.1 as well as by Mabhaudhi *et al.* (2019), Nhamo *et al.* (2020a) and Nhamo *et al.* (2020b).

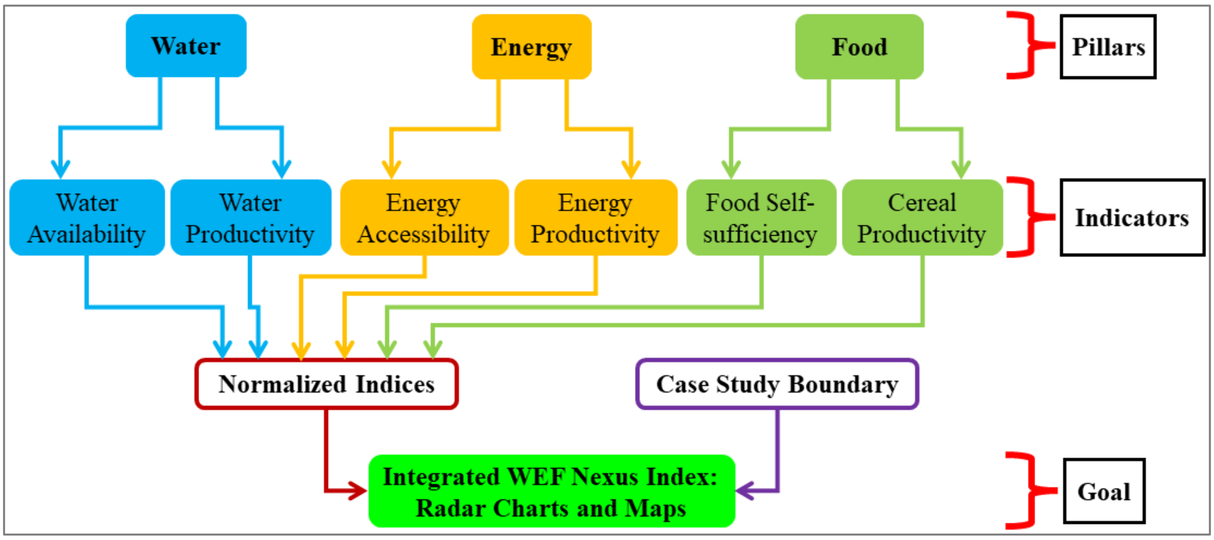

Figure 3.2: The conceptual model for iWEF

Related to the conceptual model is the flow of data for the iWEF modelling tool between the four major sub-modules: the database, user interface, computations and results (Figure 3.3).

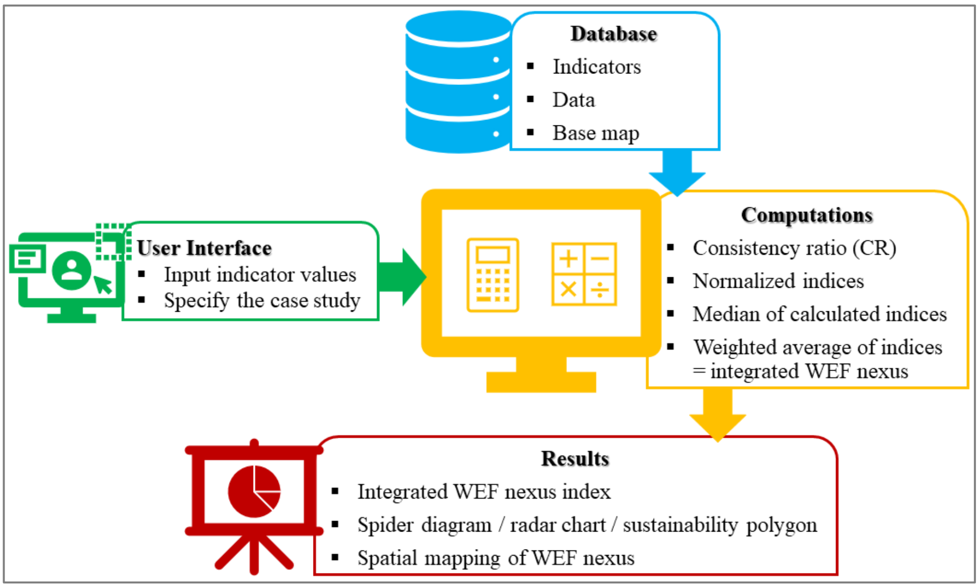

Figure 3.3: The mode of operation for iWEF using the modelling tool's sub-modules

These four components work harmoniously to enable the iWEF modelling tool to fulfil its functional expectations. Generally, the GUI allows users to interact with the iWEF database and specify the WEF nexus input data (indicators) for their study. The computation module transforms the indicators into useful results displayed as tables, graphs, and maps for interpretation and further analysis. The iWEF model is also expected to automatically determine the consistency of provided input (PCM and either accept if the consistency ratio (CR) value is less than 0.1 (or 10%) or reject if the CR value is above 0.1 (or 10%). A key feature in the iWEF model is the comparison and visualization of results for several case studies using spider diagrams and WEF nexus maps plotted and drawn 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)

The iWEF tool integrates the six WEF indicators through the AHP multi-criteria decision-making (MCDM) approach (Brunelli, 2015) by normalising WEF indicators data to determine composite indices used to compute the weighted average WEF nexus 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 at a time using Saaty's scale, which ranges between one and nine (Saaty, 1987), as indicated in the iWEF user manual (Taguta *et al.*, 2022c).

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):

$$CR = \frac{CI}{RI} \qquad \text{(Equation 3.1)}$$

where: *CI* is the consistency index, and *RI* is the random index which depends on the order n of the matrix in Table 3.1 by Saaty and Vargas (2012).

Table 3.1: Average random consistency index (RI)

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

Source: Saaty and Vargas (2012)

CI is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{(Equation 3.2)}$$

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

$$\lambda_{max} = \sum_{i=1}^{n} Cv_{ij} \qquad \text{(Equation 3.3)}$$

where: Cv_{ij} is calculated by multiplying the pairwise comparison matrix (C_{ij}) by the weights vector and then dividing the weighted sum vector with criterion weight (W_{ij}) as in (Teknomo, 2006), Vargas (2010), Bunruamkaew (2012), and Mu and Pereyra-Rojas (2017):

$$Cv_{ij} = \frac{1}{W_{ij}} \sum_{ij}^{n} C_{ij} W_{ij} \qquad \text{(Equation 3.4)}$$

According to Saaty and Vargas (2012), a 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 (Saaty and Vargas, 2012).

3.2.3.2 Calculation and normalisation of indices by AHP-MCDM technique

The AHP computes the indices for the indicators by taking the eigenvector corresponding to the largest eigenvalue of the matrix and then normalising the sum of the components (Nhamo *et al.*, 2020a). The overall importance of each indicator is then determined. The matrix, *A*, of *n* criteria, is determined using Saaty's scaling ratios in the order *(n X n)* (Saaty, 1990). As adopted in Nhamo *et al.* (2020a) and Nasrollahi *et al.* (2021), *A* is a matrix with elements aji, which is the decision maker's preference of the i^{th} criterion over the j^{th} criterion. The matrix's reciprocity is expressed as:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad \text{(Equation 3.5)}$$

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

After generating this matrix *A*, it is then normalized as a matrix *B* with elements b_{ji}, constructed by dividing each element of *A* by its column sum and expressed as in Nhamo *et al.* (2020a) and Nasrollahi *et al.* (2021):

$$B = \begin{bmatrix} \frac{a_{11}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{12}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{1n}}{\sum_{t=1}^{n} a_{tn}} \\ \frac{a_{21}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{22}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{2n}}{\sum_{t=1}^{n} a_{tn}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{a_{n1}}{\sum_{n=1}^{n} a_{n1}} & \cdots & \cdots & \frac{a_{nn}}{\sum_{t=1}^{n} a_{tn}} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \qquad \text{(Equation 3.6)}$$

Each weight value w_i in matrix W is computed by averaging across the rows of B as in Nhamo *et al.* (2020a) and Nasrollahi *et al.* (2021):

$$W = \frac{1}{n} \begin{bmatrix} \sum_{n=1}^{n} b_{1n} \\ \sum_{n=1}^{n} b_{2n} \\ \cdots \\ \sum_{t=1}^{n} b_{nt} \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} \qquad \text{(Equation 3.7)}$$

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

The iWEF model determines the integrated WEF nexus as a weighted average whose value ranges from zero to one and can be interpreted on its level or class of sustainability (Table 3.2) (Nhamo et al. (Nhamo *et al.*, 2020a).

Table 3.2: WEF nexus indices performance classification categories

WEF nexus composite index (i)	Category and interpretation			
	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
	$0 \leq i < 0.1$	$0.1 \leq i < 0.25$	$0.25 \leq i < 0.65$	$0.65 \leq i \leq 1$

Source: Nhamo *et al.* (2020a)

The value of the integrated WEF nexus represents the overall performance of resource development, utilisation, and management as seen together (Nhamo *et al.*, 2020a).

3.2.4 Development of the iWEF web-based and GIS-linked 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), allowing 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 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 with 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. The web-based and GIS-enabled iWEF model was developed with two common tasks: the back and 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 (WEF nexus 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 was 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 user manual (Taguta *et al.*, 2022c). The final outputs include a weighted average index (the nexus), a spider (radar) 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 illustrates and compares sectors' performance regarding sustainable or unsustainable management (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b).

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' (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 3.4).

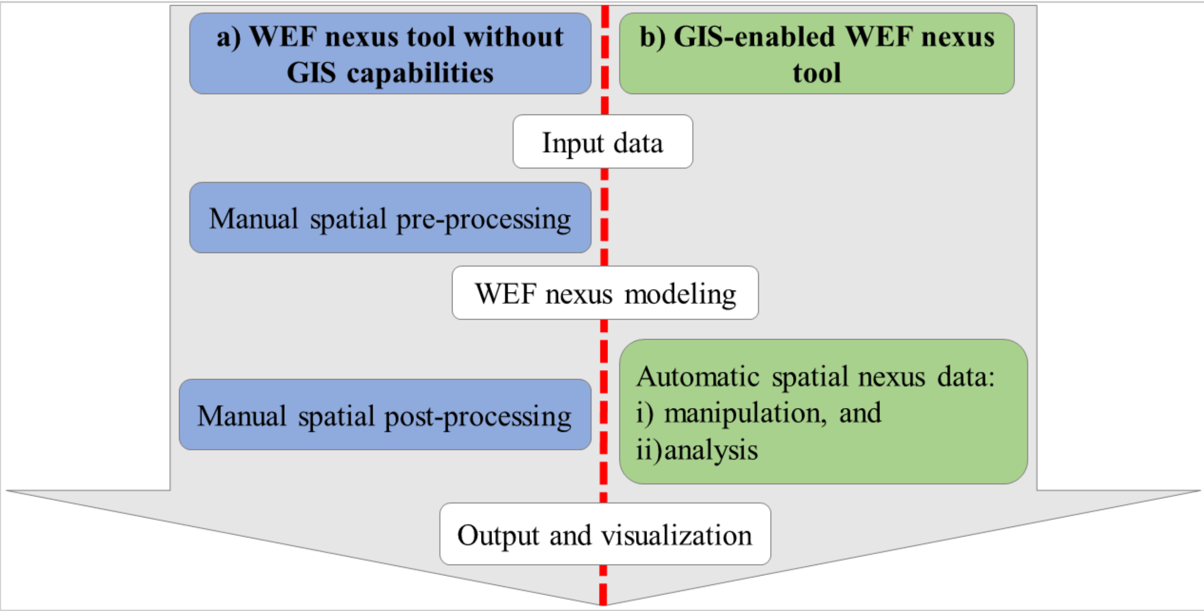

Figure 3.4: Differences in WEF nexus spatial analysis using a typical (a) left side – WEF nexus tool that uses soft-linked integration with GIS and (b) right side – GIS-enabled hard-linked WEF nexus tool. (Adapted from (Burger, 2018; Burger and Abraham, 2020)).

In this study, the iWEF model was integrated into GIS by hard-linking to an open-source base map so that users can locate their case studies, 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 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. iWEF tool was GIS-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. Leaflet can be used with several plugins that provide open-source base maps. Dash-Plotly enables users to select interactively different study areas under investigation and display and compare their WEF nexus results.

3.2.4.4 Online deployment of the iWEF modelling tool

The iWEF model (Taguta *et al.*, 2022b) was deployed on the internet on a dedicated website (https://iwef.app) with a Secure Sockets Layer (SSL) 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.

3.2.4.5 Operating procedure for the iWEF modelling tool

To operate iWEF, users must chronologically follow the steps presented in Figure 3.5.

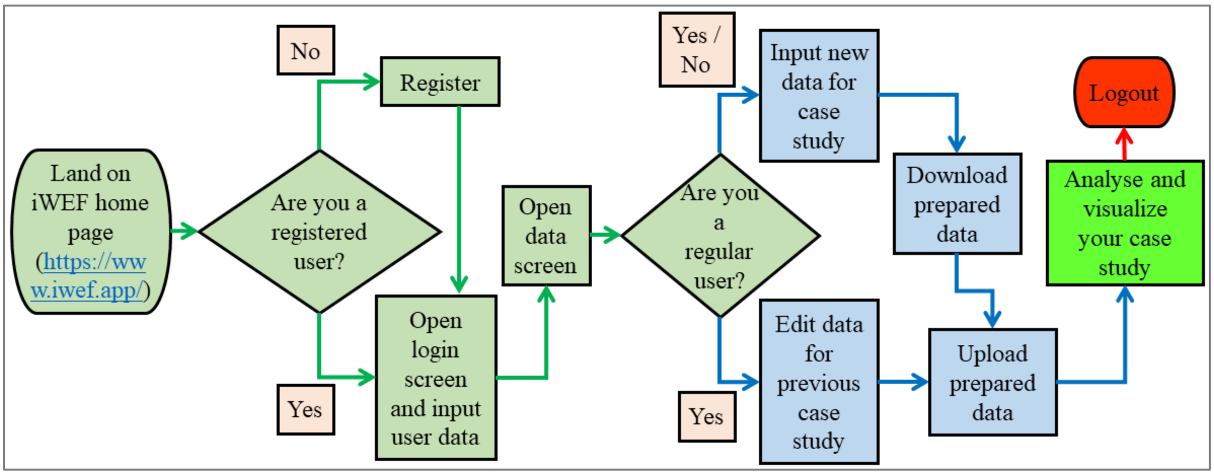

Figure 3.5 The user flowchart for the iWEF modelling tool

Users can familiarise themselves with iWEF and learn how to use iWEF through instructions, guides, and preloaded sample data, analysis, and interpretation by clicking the ‘Help’ tab. On visiting iWEF’s web page, users are prompted to register for a personal account with a unique username and password stored in the system database. These will be used as their unique identity whenever they access the iWEF modelling tool to locate their study area, capture input data, compute the WEF nexus, display, analyse, interpret, compare results, or retrieve previous case study's data and results. Step-by-step details on how to easily and successfully use iWEF are provided in the user manual (Taguta *et al.*, 2022c). Alternatively, users can watch the video tutorial in the final production phase and whose link will be provided on public platforms.

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 WEF nexus index.

3.2.5.1 Browsers compatibility and screen resolutions

The iWEF model was tested for loading and execution in Microsoft Edge (v99.0.1150.36), Google Chrome (v99.0.4844.51) and Mozilla Firefox (97.0.1)web browsers. The model was also tested for compatibility on a laptop, desktop smartphone and tablet.

3.2.5.2 Calibrating the iWEF model for accuracy of CR value

Two pairwise comparison matrix datasets were randomly generated to test the accuracy of the iWEF model 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; Vargas, 2010; Bunruamkaew, 2012; Mu and Pereyra-Rojas, 2017). The typical inconsistent and consistent pairwise comparison judgement datasets are presented in Table 3.3.

Table 3.3: Typical inconsistent and consistent pairwise comparison judgement datasets

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficien-cy	Cereal produc-tivity
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
Cereal productivity	1.00	1.00	3.00	0.20 **(0.50)**	0.14	1.00

Key: bold values belong to the consistent PCM

The two different PCMs were run in the iWEF model, and the results were compared with those from the simple web-based AHP Priority Calculator (AHP Online System – AHP-OS) by Goepel (2022).

3.2.5.3 Validating the iWEF model for the WEF nexus index

The initial version of the web-based and GIS-enabled iWEF model was tested with input from three case studies that previously applied iWEF's predecessor, i.e. the MS Excel-based tool (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 MS Excel-based tool was previously used. 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.

3.2.6 Browsers compatibility and screen resolutions

The iWEF model 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 model 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, electronic devices, and gadgets.

3.2.7 Calibration of the iWEF model for CR value

The results from running inconsistent and consistent pairwise matrix 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 Table 3.4.

Table 3.4: Results from testing for accuracy of CR value

Tool	**CR Value**	
	Inconsistent Dataset	**Consistent Dataset**
iWEF Modelling Tool	0.31	0.07
AHP Online System (AHP-OS)	0.31	0.07

Table 3.4 shows that the iWEF model is accurate and reliable in determining the CR value because its results were like those from the AHP Online System (AHP-OS). Thus, the iWEF model 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.

3.2.8 Validation of the iWEF model for the WEF nexus index

The integrated WEF nexus index from the iWEF model and its predecessor were similar to the southern Africa regional case study by Mabhaudhi *et al.* (2019) for 2017, as illustrated in Figure 3.6. The iWEF model offers the extra benefit of locating the case study area and spatially mapping and visualizing the WEF nexus (Figure 3.6c). These features are lacking in the original MS Excel-based tool. Detailed analysis and interpretation of the normalised indices and the integrative WEF nexus index are available in Mabhaudhi *et al.* (2019). The results show that managing the WEF nexus in the southern African region is marginally sustainable. Regional efforts need to be focused more on nexus solutions that enhance water (productivity and availability), energy (accessibility and productivity), and cereal productivity.

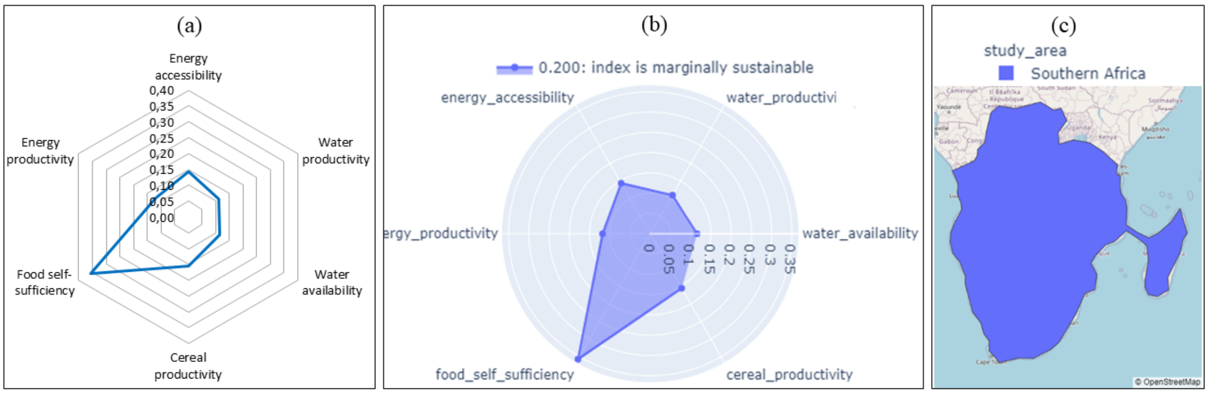

Figure 3.6: WEF nexus analysis results with a value of 0.200 at the regional scale for southern Africa (a) quantitatively using the MS Excel-based tool (Mabhaudhi *et al.*, 2019), (b) quantitatively using the iWEF modelling tool, and (c) spatially using the iWEF modelling tool.

For the South Africa national case study by Nhamo *et al.* (2020a) for 2015, the iWEF model reproduced the quantitative, visual and graphical results similar to the MS Excel-based tool (Figure 3.7). Additionally, the iWEF model spatially characterised the WEF nexus (Figure 3.7c), a characteristic absent in the original MS-Excel-based tool. Detailed analysis and interpretation of the normalised indices and the integrative WEF nexus index are available in Nhamo *et al.* (2020a). The management of the WEF nexus in South Africa is marginally sustainable, with room for improving citizens' access to energy, water availability and cereals' productivity.

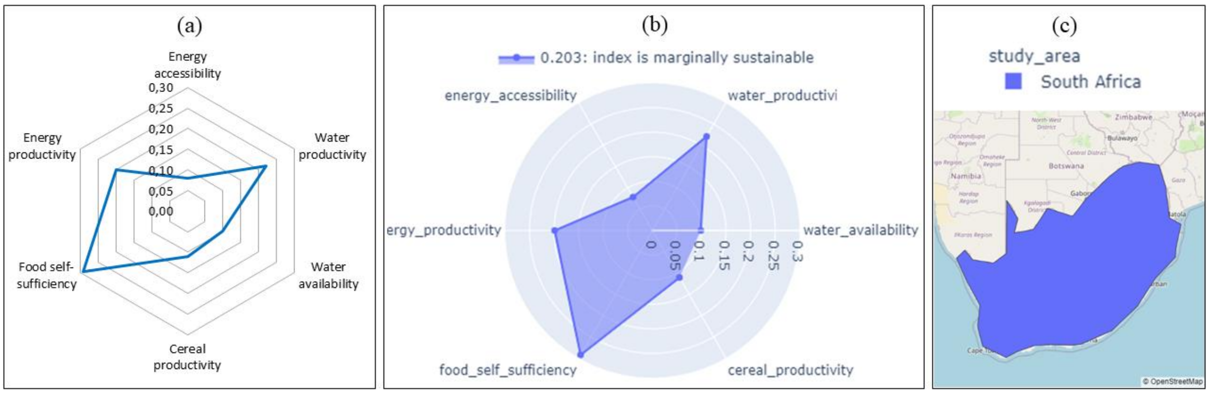

Figure 3.7: WEF nexus analysis results with a value of 0.203 at the national scale for South Africa (a) quantitatively using the MS Excel-based tool (Nhamo *et al.*, 2020a), (b) quantitatively using the iWEF modelling tool, and (c) spatially using the iWEF modelling tool.

The iWEF model produced results similar to the original MS Excel-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 3.8. Unlike the MS Excel-based tool, the iWEF modelling tool managed to spatially map and visualize the WEF nexus (Figure 3.8c). Detailed analysis and interpretation of the normalised indices and the integrative WEF nexus index are available in Nhamo *et al.* (2020b). At this local scale, management of the WEF nexus is marginally sustainable. The municipality needs to explore nexus-relevant interventions that improve water availability, energy accessibility and cereal productivity.

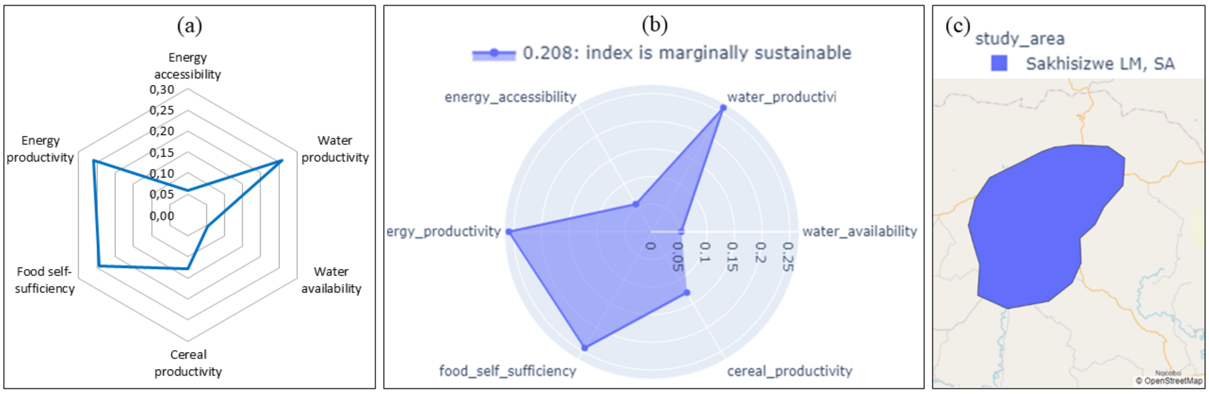

Figure 3.8: WEF nexus analysis results with a value of 0.208 at the local municipal scale for Sakhisizwe Local Municipality (South Africa) (a) quantitatively using the MS Excel-based tool (Nhamo *et al.*, 2020b), (b) quantitatively using the iWEF modelling tool, and (c) spatially using the iWEF modelling tool.

The iWEF modelling was also able to simultaneously analyse 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 3.9. This also showcases the iWEF modelling tool's ability to compare the WEF nexus across temporal and spatial scales, a key feature in analysing and planning WEF nexus scenarios. Although the management of the WEF nexus is marginally sustainable across the three scales, the local municipality performs relatively better, followed by the national and regional scales. This is evidence of vertical and horizontal inconsistency and incoherence of WEF-related policies and their implementation across different regional scales.

Similarly, this motivates the assessment of the WEF nexus at multiple scales for identifying champions, hotspots, opportunities, threats and relevant interventions.

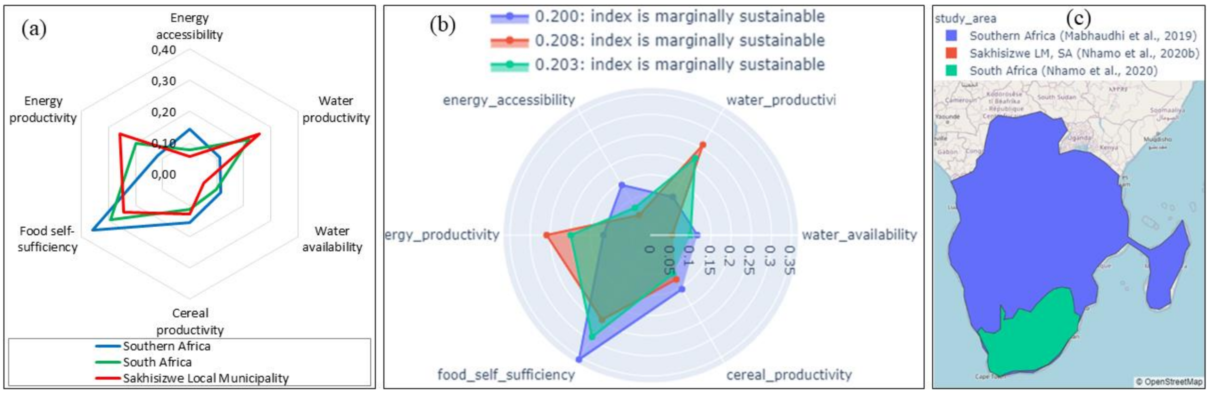

Figure 3.9: Multiple case study WEF nexus analysis results at regional (Southern Africa), local municipal (Sakhisizwe), and national (South Africa) scales (a) quantitatively using the MS Excel-based tool (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2020b), (b) quantitatively using the iWEF modelling tool, and (c) spatially using the iWEF modelling tool.

Thus, the iWEF modelling tool is compatible with common web browsers, gadgets and devices. From the instances of testing, verification and validation in this study, it can be safely concluded that the web-based GIS-enabled iWEF model is accurate in computing and presenting the WEF nexus at multiple scales. It can check the consistency and randomness of pairwise comparison judgements and thus inform users on the quality of their input data. Thus, the iWEF model can confidently be used in other case study areas of interest to characterise the WEF nexus. This confirms that computational modelling is a powerful tool for quantifying interactions within the WEF nexus and aiding sustainable decision-making, as postulated by Bieber et al. (2018).

3.3 Conclusions

This study introduced a user-friendly, freely accessible, web-based and GIS-enabled integrative WEF nexus analytical model, iWEF. The developed tool is GIS-enabled through a ‘hard-linked’ GIS integration of the WEF nexus model with open-source base maps. The motivation to locate the tool on the web is for easy, free and open-source availability, accessibility and usability by the public. The interested users are in academia, research, management, planning, policy- and decision-making. The iWEF modelling tool was tested for accuracy in computing CR values and the integrated WEF nexus index. The tool accurately and reliably determined the CR values and the WEF nexus index, with an additional ability to spatially map and visualize the WEF nexus.

Key outputs in iWEF include a spider graph (radar chart or sustainability polygon) of normalised indices and maps. The shape of the radar chart illustrates WEF nexus indicator performance and inter-relationships, providing a synopsis of the level of interactions, interdependencies, and inter-connectedness among WEF nexus sectors, whose management is perceived as either sustainable or unsustainable. The maps show the spatial distribution of the WEF nexus in the locations of interest, thus highlighting the hotspots and champions. The iWEF model can display radar charts and map results for multiple case studies, allowing for scenario planning and analysis. The tool needs to be embedded as a planning tool in the day-to-day operations of policy- and decision-makers to bring together water, energy and agriculture sectors.

As a starting point, the GIS-based tool (iWEF) can act as an ancillary assessment and decision-making instrument for the composition of informed policies and responsible investments for transformational growth. The WEF nexus tool’s analysis of the WEF nexus at different scales encourages horizontal and vertical cooperation and coordination within and between different departmental sectors in developing integrated policies and decision-making. This is crucial when undertaking site selections for proposed developments and determining the possible impacts on WEF nexus interactions and sustainability. Thus, the iWEF model contributes to closing the gap between the WEF nexus theory and actual practice by supporting and informing the implementation of the WEF nexus approach. 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 model for compatibility and convenience with various users and devices (gadgets). Other recommended improvements for the iWEF model 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. The indicators in the current version of iWEF are more quantitative than qualitative. Hence, going forward, some of the indicators in the iWEF modelling tool should reflect on qualitative aspects of WEF resources, for example, water sources (surface, ground, unconventional) and quality, nutrition, and proportions or a mix of different energy technologies such as renewable. Such indicators have a bearing on the road towards sustainable development.

4 APPLICATION OF THE MODEL AT THE REGIONAL LEVEL FOR ASSESSING RURAL LIVELIHOODS

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4.1 Introduction

Water, energy and food are vital resources for human well-being, poverty reduction and sustainable development (McMichael *et al.*, 2006; Rasul and Sharma, 2016). Demand for these scarce and depleting natural resources is projected to increase significantly in the near future due to societal, environmental, technological, economic and demographic changes, thereby threatening their sustainability and undermining the resilience, livelihoods and wellbeing of communities (Corvalan *et al.*, 2005; Gelsdorf, 2010). The resultant challenge requires transdisciplinary and transformative approaches in resource management, development and utilisation, using integrative approaches such as the water-energy-food (WEF) nexus, which allows for inclusive and equitable development and coordinated resource planning and management (Nhamo *et al.*, 2018).

This chapter presents how the WEF nexus analytical model developed by (Nhamo *et al.*, 2019c) was used to develop a WEF Nexus Analytical Livelihoods Framework (ALF), which was used to analyse and address the complex and interrelated nature of resource systems for improving rural livelihoods and climate change adaptation (Nhamo *et al.*, 2019c). The WEF Nexus ALF is a systems approach that analyses and assesses the interactions between the natural environment and the biosphere, facilitating more coordinated management and monitoring of resources (Nhamo *et al.*, 2018). As the WEF Nexus ALF monitors the performance of resource development, it is also essential for assessing the performance and progress of Sustainable Development Goals (SDGs) that are directly related to the WEF nexus (Goals 2, 3, 6 and 7). The WEF nexus analytical model was used to assess resource utilisation and performance in southern Africa, in the context of achieving the 2030 Global Agenda of

SDGs, that is, how best to build resilient rural communities and enhance sustainable rural livelihoods.

4.2 Materials and methods

4.2.1 The study area

The study focused on southern African countries, mainly Angola, Botswana, Comoros, Democratic Republic of Congo (DRC), Lesotho, Madagascar, Mauritius, Malawi, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe (Figure 4.1).

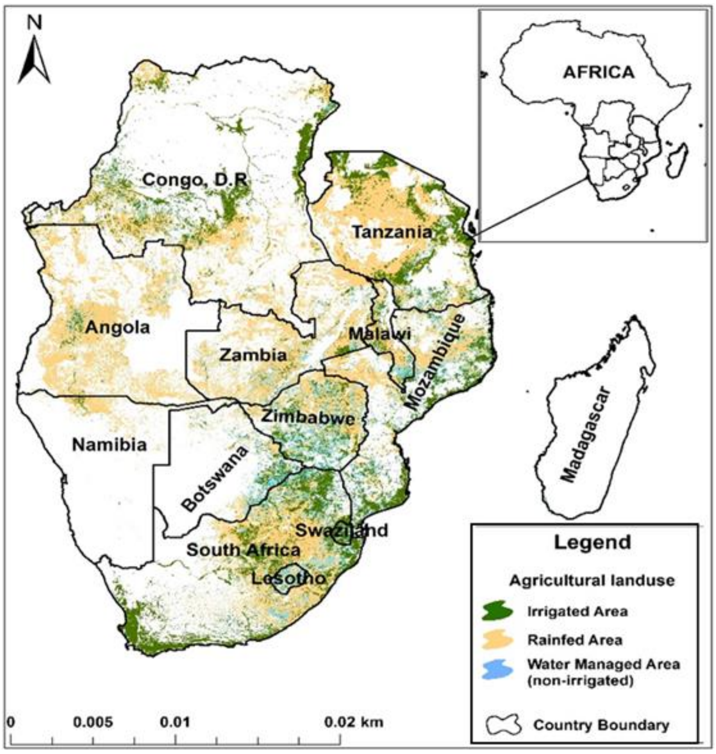

Figure 4.1: Locational map of southern Africa showing the distribution of agricultural systems. Cultivation is concentrated in countries in the east, whereas to the west, Botswana and Namibia have the least cultivated land due to arid conditions. Source: Adapted from IWMI irrigated area mapping (IWMI, 2010).

The same 16 countries form a regional economic bloc known as the Southern African Development Community (SADC). Agriculture is the main source of livelihood for the generally rural population, contributing about 17% to regional GDP (increasing to above 28% when middle-income countries are excluded (Mucavele, 2013; SADC, 2014). The SADC Treaty is the overarching regional policy framework that aims to achieve economic development, peace and security, alleviate poverty and improve the people's livelihoods through regional integration (SADC, 2011). To strengthen its agrarian economy, the region intends to increase agricultural production by increasing the irrigated area. Increasing agricultural production is envisaged to result in surplus yields that households of comparative advantage can supply regions of less potential, thereby ensuring food security and improving livelihoods. In this regard, the region intends to double the irrigated area from 3.5 to 7% by 2025 (SADC, 2014).

Although irrigation potential in southern Africa is very high, agriculture remains rainfed (Figure 4.1). Land with irrigation potential is about 20 million ha, yet only 3.9 million ha is equipped for irrigation, accounting for approximately 6.6% of the total cultivated area (IWMI, 2010; Nhamo *et al.*, 2019d). Figure 4.1 also shows the distribution of agricultural systems in the region. The vision to increase irrigated areas targets the smallholder farming sector because of its importance in food security and high vulnerability to climate variability and change. Despite the huge agriculture potential and a big domestic market for agricultural products, poverty levels remain high, particularly in rural areas (Nhamo *et al.*, 2018). The regional population stands at 342 million, of which 70% live in rural areas (Nhamo, 2015).

4.2.2 The methodological framework

Managing water, energy, and food resources as an interconnected system and eliminating the traditional silo-based planning improves sustainable development through research-based evidence (Díaz *et al.*, 2015; Endo *et al.*, 2017; Dargin *et al.*, 2019). The basis of the WEF nexus approach to resource management lies in identifying and justifying the interactions at the multiple interfaces of resource systems while holistically assessing the impact of specific contexts or interventions from the environmental, financial, and socio-cultural perspectives (Daher *et al.*, 2018). From this systems perspective, Figure 4.2 is presented as a methodological framework focusing on improving rural livelihoods and health in the advent of climate variability and change. Figure 4.2 represents the components of the WEF Nexus Analytical Livelihoods Framework (ALF) from systems thinking perspective.

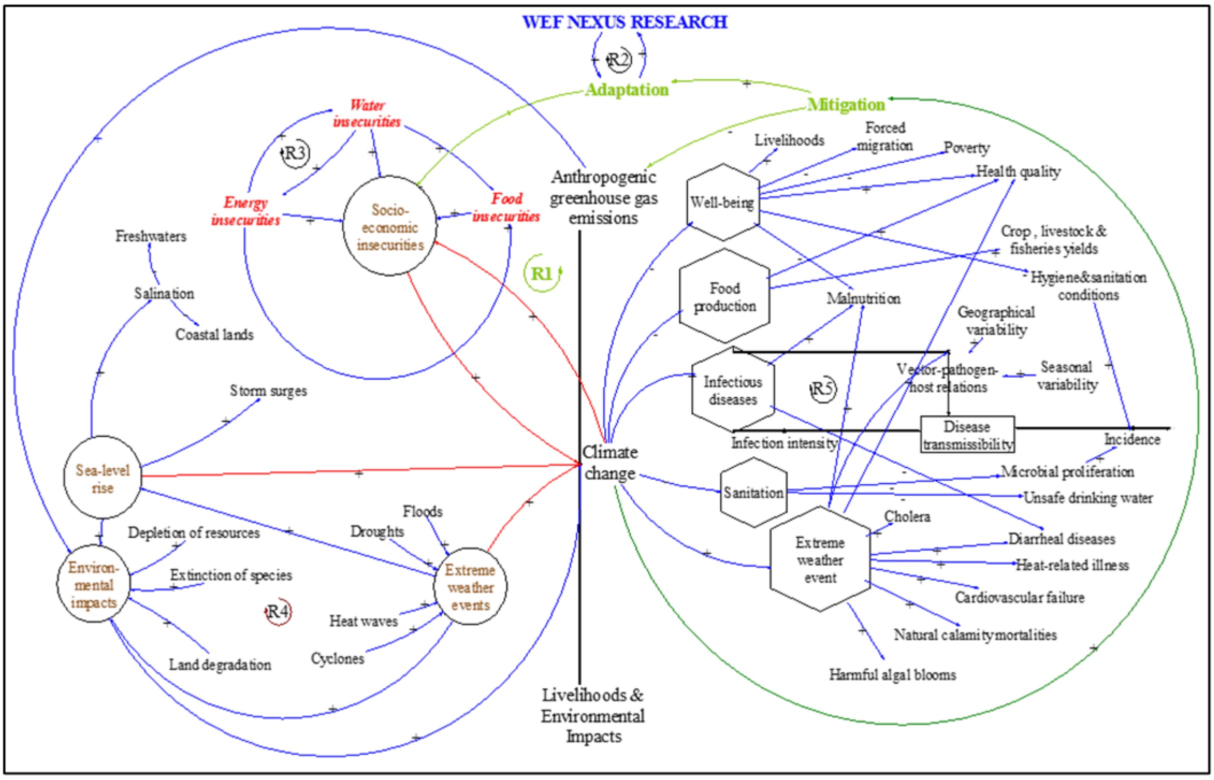

Figure 4.2: A systemic representation of the WEF Nexus Analytical Livelihoods Model showing the system's multi-dimensionality interactions and feedback effects. The left enclosure shows measurable system components (encircled) related to climate change. The right enclosure shows the impact of climate change (diamond-shaped) with vicious cascading effects on livelihood and health.

The WEF Nexus ALF is adapted from the work done by (McMichael *et al.*, 2006), which depicts the pathways by which climate change can affect population health. Several climatic-environmental manifestations of climate change are shown, which altogether portray an increased complexity of causal processes having environmental consequences and, therefore, the likelihood that health effects will be deferred or protracted. To elicit the linkages among the causes and the effects of climate, we converted McMichael’s schematic summary of the main pathways by which climate change affects population health into a causal loop diagram (CLD) shown in Figure 4.2. The system approach integrates water, food and energy aspects by mapping key elements of the subsystems and visualising their interdependencies.

The aim is to build livelihood resilience through the WEF nexus by considering the linkages between WEF resources and causal mechanisms (Byers, 2015). Improving livelihoods and social equality requires inclusive participation by all in decision-making through consultation (Rasul, 2016). Faced with the realities of climate change and how they are impacting mainly the rural poor, there have been loud calls to reduce greenhouse gas (GHG) emissions, which is the major cause of accelerated climate change (Bulkeley *et al.*, 2014; Preston *et al.*, 2014). For example, the Paris Climate Agreement brings the globe into a common cause of undertaking ambitious efforts to combat climate change and adapt to its effects by keeping a global temperature rise this century well below two °C above pre-industrial levels and assisting developing countries in achieving climate change adaptation (Zhang *et al.*, 2017; Clark, 2018).

The first part of the study relates to the impacts of climate change on WEF resources and proposes mitigation strategies through the WEF Nexus ALF. As people in rural areas generally depend on natural systems for their livelihood, availability and accessibility to land and other natural resources are crucial for survival. Then secondly, the study demonstrates how the WEF nexus can be used as a decision support tool in addressing pertinent issues, mainly transforming livelihoods and sustaining the environment. The premise is that resilience and adaptation must be decoupled from extensive use and depletion of natural resources and environmental damage and promote sustainable means of production, investments and consumption, along with enhanced resource efficiency and the reduction of waste, food losses and pollution (Mensah and Castro, 2004). Adaptation through the WEF nexus ensures that vulnerable and marginalised populations are empowered by removing barriers that hinder balanced resource sharing and inclusive economic development (Mpandeli *et al.*, 2018). Specific challenges brought about by climate variabilities and change, such as extreme weather events and resource depletion (Figure 4.2), are addressed by strengthening resilience at the local and community level. Thus, the first and second parts of the methodological framework (Figure 4.2) emphasise mitigation and adaptation. Mitigation is tackling the root cause of climate change to alleviate further damage to the atmosphere. Adaptation deals with the impact of climate change, such as extreme weather events and the depletion of resources (Ming *et al.*, 2014).

The third part addresses the health effects of climate change (Figure 4.2). It applies the WEF Nexus Analytical Livelihoods Framework to understand the causes and effects on human well-being and develop guidelines to alleviate the health effects of climate change. Environmental sustainability and human well-being are linked to conserving nature and natural resources and preserving biodiversity and ecosystem services. The WEF nexus is important in guiding decision-making (Biggs *et al.*, 2015; Fürst *et al.*, 2017). Sustainable use and management of natural resources through the WEF nexus ensure water, energy and food security, equitable public goods and services supply, and inclusive development (Nhamo *et al.*, 2018). Thus, sustainable livelihood transformation cannot be separated from climate change adaptation and WEF nexus-based research, as the approach is a “fitting tool” in transforming livelihoods, providing evidence to policy and decision-making in adaptation strategies.

The CLD shown in Figure 4.2 explains the WEF Nexus Analytical Livelihoods Framework and explains the complex interrelationships among resources for livelihoods transformation, human health and well-being. The CLD provides a visual representation of multiple, interdependent effects of climate change and human actions on WEF resources. The Vensim PLE x32 software (www.ventanasystems.com) was used to develop the CLD for the WEF Analytical Livelihoods Framework. The CLD is a qualitative representation of the interlinkages between resource utilisation and management and their effects on livelihoods in the advent of climate variability and change. The arrows show the influence of one variable on another (a change in the cause leads to a change in the effect). The polarity of the arrows indicates the factual relationship between any two nodes, which illustrates the causal link. The interplay between balancing and reinforcing loops gives rise to a realistic multi-loop system that explains the behaviour of the WEF model and the nexus impact over time. The reinforcing loop, R1, indicates the pathway through which mitigation measures lead to adaptation, with reduced anthropogenic GHG emissions in an amplified manner between resource insecurities and climate change. R1 is the ultimate loop that the WEF nexus research has to achieve. One of the means to achieve this aim is through the ability to assess the nexus interactions (evidence-based interventions) with amplifying effects for adaptation, as in R2, which is the aim of this study. Other vicious bottlenecks in the system include R3 (the vicious reinforcing interrelationship between water, energy and food insecurities), R4 (environmental and behavioural patterns that contribute to climate change) and R5 (heightened disease transmissibility pathways).

The CLD justifies the context of the complexity of causal mechanisms within which climate change occurs and the resulting causal effects it generates on WEF resources, livelihoods and health. It sets the context for considering the indicators listed in Table 4.1 for the pairwise comparison.

4.2.3 WEF nexus sustainability indicators

Table 4.1 presents WEF nexus sustainability indicators and their pillars considered when determining WEF nexus composite indices (Nhamo *et al.*, 2019c).

Table 4.1: Indicators and sub-indicators for WEF nexus component

WEF nexus Component	Indicator	Pillars
1. Water	The proportion of available freshwater resources per capita (availability) The proportion of crops produced per unit of water used (productivity)	Affordability Stability Safety
2. Energy	The proportion of the population with access to electricity (accessibility) Energy intensity measured in terms of primary energy and GDP (productivity)	Reliability Sufficiency Energy type
3. Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency) The proportion of sustainable agricultural production per unit area (cereal productivity)	Accessibility Availability Affordability Stability

Source: Nhamo *et al.* (2019c)

Sustainability indicators for WEF nexus performance are related to accessibility, self-sufficiency, and availability and how they influence respective production (productivity) (Nhamo *et al.*, 2019c). Productivity, accessibility, self-sufficiency and availability are the major drivers of water, energy and food security from where indicators are defined. Derived composite indices are important for assessing resource performance and management at any given scale, providing policy and decision-making with valuable information on priority areas needing intervention (Nhamo *et al.*, 2019c). Thus, the use of sustainability indicators and indices is an invaluable evaluation tool of the state of resources, either in the short and/or long term, providing directions for the actions to take in an attempt to ensure resources are sustainable and, at the same time, improving livelihoods and wellbeing (Nhamo *et al.*, 2019c).

4.2.4 Overview of the WEF nexus indicators for southern Africa

The importance of the WEF nexus is to simplify human understanding of the complex relationships among the interlinked resources of water, energy and food, explain those relationships through quantitative evidence, and ensure the security of the three resources (Nhamo *et al.*, 2019c). Factors that measure resource security include availability, accessibility, self-sufficiency and productivity, from which we defined related indicators to measure the performance of WEF resources (Bizikova *et al.*, 2014; Nhamo *et al.*, 2019c). Table 4.2 lists the defined indicators for WEF resources, also providing an overview of the status of WEF nexus-related indicators for southern Africa (WorldBank, 2017).

Table 4.2: Overview of the WEF nexus indicators for southern Africa

WEF nexus component	Indicator	Indicator status 2017*
1. Water	The proportion of available freshwater resources per capita (availability)	3 984 m^3
	The proportion of crops produced per unit of water used (water productivity)	$10/$m^3$
2. Energy	The proportion of the population with access to electricity (accessibility)	42.8%
	Energy intensity measured in terms of primary energy and GDP (productivity)	7 (MJ/GDP)
3. Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency)	8%
	The proportion of sustainable agricultural production per unit area (cereal productivity)	1 395 kg/ha

Source: WorldBank (2017). **The reported indicators include both rural and urban populations.*

The selection of the indicators is based on the criteria used by (Nhamo *et al.*, 2019c), in which they considered the factors that determine resource security. A multi-criteria decision method (MCDM) was used to integrate and establish numerical relationships among WEF nexus indicators and calculate indices, applying the Analytic Hierarchy Process (AHP), which is an MCDM method (Saaty, 1977; Triantaphyllou and Mann, 1995). The AHP, developed by (Saaty, 1987), 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 at a time using Saaty's scale, which ranges between 1/9 and 9 (Saaty, 1977). A range between 1 and 9 represents an important relationship, and a range between 1/3 and 1/9 represents an insignificant relationship. A rating of 9 indicates that the row factor is 9 times more important in relation to the column factor.

Conversely, a rating of 1/9 indicates that the row indicator is 1/9 less important relative to the column indicator. In cases where the column and row indicators are equally important, they have a rating of 1. In the case of the WEF nexus, the index of an indicator in relation to others is determined by the impact of that particular indicator on its overall rating.

With the help of expert advice, the indicator status given in Table 4.2 provides the basis to establish numerical relationships among the indicators through a pairwise comparison matrix (PCM) as proposed by Nhamo *et al.* (2019c). Using the AHP, the pairwise comparison matrix (PCM) is normalised to establish the composite indices for each indicator and an integrated WEF nexus index (Nhamo *et al.*, 2019c). The indicator values shown in Table 4.2 are not disaggregated between rural and urban areas as they represent southern Africa. However, it is common knowledge that rural areas have always lagged behind urban areas regarding economic development, provision of basic services and access to resources (Baum and Weingarten, 2004). Therefore, if the performance of resource use were classified as unsustainable, it would mean a worse situation in rural areas.

4.2.5 Determining the pairwise comparison matrix and normalisation of indices

Through the PCM, the AHP calculates the indices for each indicator by taking the eigenvector (a vector whose direction does not change even if a linear transformation is applied) corresponding to the largest eigenvalue (the size of the eigenvector) of the matrix and then normalising the sum of the components (Stewart and Thomas, 2006). The eigenvalue method synthesises a pairwise comparison matrix to obtain a priority weight vector for several decision criteria and alternatives. Here an eigenvector of the matrix is used for the priority weight vector. In the eigenvector method, the priority weight vector is set to the right principal eigenvector w of the pairwise comparison matrix (Saaty, 1990). The overall importance of each indicator is then determined. The basic input is the pairwise matrix, A, of n criteria, established based on Saaty's scaling ratios, which is of the order *(n x n)* (Rao *et al.*, 1991). A is a matrix with elements a_{ij}. The matrix generally has the property of reciprocity, expressed mathematically as:

$$a_{ij} = \frac{1}{a_{ij}} \qquad (4.1)$$

After generating this matrix, it is then normalized as a matrix *B*, in which *B* is the normalized matrix of *A*, with elements b_{ij} and expressed as:

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1} n \, a_{ij}} \qquad (4.2)$$

Each weight value w_i is calculated as:

$$w_i = \frac{\sum_{j=1} n \, b_{ij}}{\sum_{i=1} n \sum_{j=1} n \, b_{ij}}, i, j = 1,2,3 \ldots, n \qquad (4.3)$$

The integrated WEF nexus index is then calculated as a weighted average of all indicator indices. The integrated composite index represents the overall performance of resource development, utilisation and management as seen together.

4.2.6 Calculating the consistency of the pairwise comparison matrix

The consistency ratio (*CR*) indicates whether the matrix judgments were randomly produced and are consistent (Alonso and Lamata, 2006). Allowable *CR* values are those ranging from 0.10 (10%). Higher *CR* values indicate that the comparisons are less consistent, while smaller values indicate that comparisons are more consistent. When *CRs* are above 0.1, the process has to be repeated (Saaty, 1977). The *CR* is calculated as (Teknomo, 2006):

$$CR = \frac{CI}{RI} \qquad (4.4)$$

where: *CI* is the consistency index, *RI* is the random index, and the average of the resulting consistency index depends on the order of the matrix given by (Saaty, 1977). *CI* is calculated as:

$$CI = \gamma - \frac{n}{n-1} \qquad (4.5)$$

where: λ is the principal eigenvalue (shaded section of Table 4.3), and n is the number of criteria or sub-criteria in each pairwise comparison matrix.

4.3 Results and discussion

4.3.1 Impacts of climate change in southern Africa

Southern Africa is highly vulnerable to climate change and variability because of multiple factors such as reliance on climate-sensitive sectors of agriculture and fisheries, lack of resources to adapt, poor infrastructure and lack of institutional arrangements, as well as low adaptive capacity (Nkomo and Nyong, 2006; Thornton *et al.*, 2014; Nhamo *et al.*, 2019a). Water, energy and food are expected to be the region's most affected sectors by climate variability and change (Mpandeli *et al.*, 2018). The largest proportions of populations vulnerable to the vagaries of climate change are found on the African continent, where chronic water, food and energy insecurity and malnourishment remain endemic (Nhamo *et al.*, 2018). Rainfall variability threatens the production of more than 80% of the continent's agricultural land, as agriculture is mainly rainfed (Besada and Werner, 2015). Climate projections for southern Africa indicate increased physical and/or economic water scarcity by as early as 2025 (Boko *et al.*, 2007). The Intergovernmental Panel on Climate Change (IPCC) estimates that between 75-250 million people and 350-600 million people in Africa will be at risk of increased water stress by 2020 and 2050, respectively (Parry *et al.*, 2007) (Figure 4.3). Reduced rainfall, coupled with increased temperatures, will reduce (a) the area suitable for agriculture, (b) the length of the growing period and (c) yield potential (Parry *et al.*, 2007; Nhamo *et al.*, 2019d). By 2080, rainfall variability and longer dry spells would result in a reduction of crop yields rise in sea levels, and coastal and low-lying areas would be affected by floods. Significant changes are already being experienced in sectors of agriculture, water, energy, biodiversity and health (Niang *et al.*, 2014) (Figure 4.3). Climate models predict that Africa will be able to provide only 13% of its food requirements by 2050 if no measures are in place to reduce GHG emissions (Niang *et al.*, 2014). The population is anticipated to have increased to 2 billion during the same period. Current statistics indicate that only 290 million out of 915 million people have access to electricity, and the total number without access is rising due to increased population growth and a lack of contingency plans to improve the current situation (IEA, 2014). Extreme weather events caused by climate change derail the progress made so far in poverty alleviation, employment, housing, access to and provision of services, food security and potable water (Thornton *et al.*, 2014).

Climate change will also increase vector-borne diseases (Figure 4.3), such as malaria, dengue fever, and yellow fever (Githeko *et al.*, 2000; Mpandeli *et al.*, 2018).

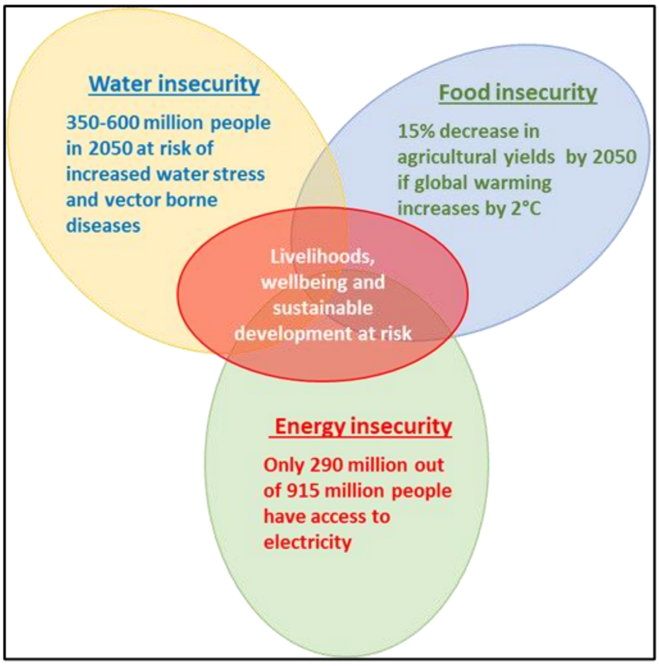

Figure 4.3: Summarised highlights of projected climate change risks on WEF resources for sub-Saharan Africa as highlighted in the text.

Health challenges caused by climate change will be highly noticeable in regions experiencing extreme weather events like heatwaves, floods, storms and fires. Other health risks resulting from climate change will be changes in regional food yields, disruption of fisheries, loss of livelihoods, population displacement due to sea-level rise, water shortages, and loss of agricultural land, among others (Ali *et al.*, 2017). Water, energy and food security are closely related to health, as food and water, for instance, have a direct impact on human health and the physical conditions of humans strongly influence their ability to work (Wlokas, 2008).

Climate change models project that warming over the African continent is occurring at twice the global rate (Niang *et al.*, 2014; Engelbrecht *et al.*, 2015). Without actions to reduce greenhouse gas emissions (GHG), temperatures are projected to rise more than 4°C in southern Africa by 2100. Using the 1981-2000 base period, heatwaves have increased by over 3.5-fold to date in the region (Ceccherini *et al.*, 2017; Dosio, 2017). Such changes in climate regimes, coupled with increased frequency and intensity of floods and droughts, are usually accompanied by health issues. The effects of extreme weather events transcend mortality and damage to property and crops but also result in food and water insecurity, the spread of disease and mental health conditions (Machalaba *et al.*, 2015).

4.3.2 WEF Nexus Analytical Livelihoods Framework

Adaptation strategies are wide-ranging in nature and can be conceptualised broadly along a continuum, varying from interventions that are exclusively designed to mitigate the impacts associated with a changing climate to initiatives aimed at addressing the wider underlying drivers of vulnerability and adaptive capacity (Jones *et al.*, 2010). Adaptation depends on the adaptive capacity of a household or community, which is generally lacking in most rural communities of southern Africa (Piya *et al.*, 2012; Nhamo *et al.*, 2019a). Adaptive capacity is the ability of a system to adjust to climate change and accommodate shock or stress or to expand the scope of variability with which it can cope (Jones *et al.*, 2010). The adjustments include controlling potential damage, taking advantage of opportunities, coping with consequences, expanding the coping range and reducing vulnerability (Jones *et al.*, 2010).

Climate change adaptation refers to changes in processes, practices, or structures to offset potential damages or take advantage of climate change opportunities (IPCC, 2001). It encompasses actions that minimise the vulnerability of households, communities and regions to climate change. Although adaptation can be spontaneous or planned, its success is determined by institutional and analytical frameworks that oversee and assess vulnerability and adaptive capacity (Jones *et al.*, 2010). The WEF Nexus Analytical Livelihoods Framework ensures integrated management of resources and public services while simultaneously considering synergies and trade-offs at all scales (Leck *et al.*, 2015). The transformation of rural livelihoods and the sustainability of adaptation strategies are underpinned by understanding the WEF nexus's role in framing effective policies and institutions. Figure 4.4 represents a WEF nexus adaptation framework for assessing, monitoring and improving resource utilisation and management to ensure sustainable livelihood transformation.

The first component of the framework (Figure 4.4) depicts the WEF nexus as a tool to enhance climate change adaptation and resilience for sustainable livelihoods in the environment (Biggs *et al.*, 2015).

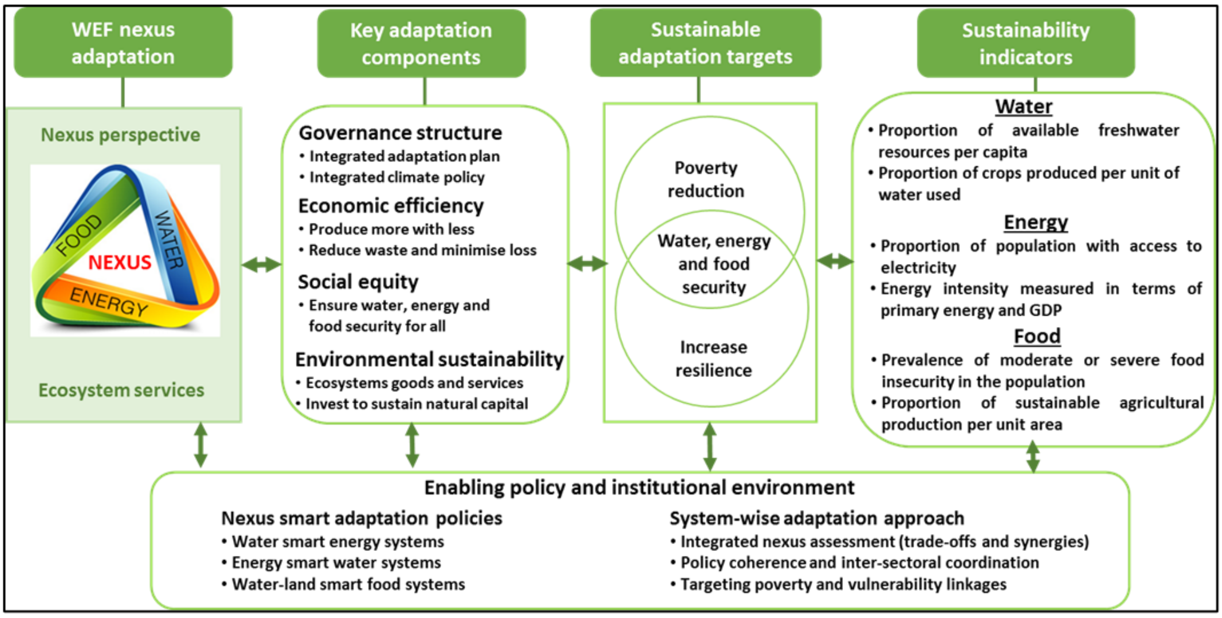

Figure 4.4: WEF nexus livelihoods adaptation and transformation framework

It illustrates the intricacies of the interlinkages among the WEF nexus sectors. These envisaged outcomes are achieved through the key adaptation strategies of governance (policies and plans), social equity (accelerating access for all), environmental sustainability (investing in sustaining ecosystem services) and economic efficiency (increasing resource efficiency), as shown in the second component (Rasul and Sharma, 2016). These four key adaptation components form the basis to meet sustainable targets of reducing poverty and building resilience, which result in the security of resources and sustainable development. The targets define sustainability indicators (the last component of the framework) that assess and monitor resource planning and management and ensure equitable resource distribution and inclusive development. WEF nexus sustainability indicators are measurable parameters that indicate the performance of resource development and monitor how the development impacts livelihoods or vice-versa (Nhamo *et al.*, 2019c). The essence of the indicators is to connect statements of intent (objectives) and measurable aspects of natural and human systems. The four components of Figure 4.4 are supported and underpinned by an enabling environment that oversees the WEF nexus implementation (Rasul and Sharma, 2016).

4.3.3 Pairwise comparison matrix for WEF nexus indicators for southern Africa

The PCM for WEF nexus components for southern Africa is given in Table 4.3.

Table 4.3: Pairwise comparison matrix for WEF nexus indicators for southern Africa

Indicator	**Pairwise comparison matrix**					
	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity
Water availability	1	1/3	1/3	1	1	1
Water productivity	3	1	1/3	1/3	1/3	1
Energy accessibility	3	3	1	1	1/5	1/3
Energy productivity	1	3	1	1	1/3	1/3
Food self-sufficiency	1	3	5	3	1	7
Cereal productivity	1	1	3	3	1/7	1

The diagonal elements are the values of unity (i.e. when an indicator is compared with itself, the relationship is 1). Since the matrix is also symmetrical, only the lower half of the triangle is filled in, and the remaining cells are reciprocals of the lower triangle. As already alluded to, the relationships are established using a scale ranging between 1/9 and 9, as given by (Saaty, 1977). An overview of the regional indicator status for 2017 is shown in Table 4.2. The classification categories given in Table 4.5 also provide the basis for scaling the relationships. Thus, the indicator values are given in Table 4.2, and their classifications provide the basis for classifying the indicators.

4.3.4 WEF nexus composite indices for southern Africa

Composite indices for each indicator from the normalised PCM for southern Africa are indicated in Table 4.4, as calculated using Equation 4.3. Table 4.4. also provides the WEF nexus integrated index, which is 0.145, a low index which reveals the unsustainability in performance of resource utilisation and management in the region according to the classification by (Nhamo *et al.*, 2019c).

Table 4.4: Normalised pairwise comparison and composite WEF nexus indices for southern Africa

Indicator	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity	Indices
Water availability	0.100	0.029	0.031	0.107	0.332	0.094	0.116
Water productivity	0.300	0.088	0.031	0.036	0.111	0.094	0.110
Energy accessibility	0.300	0.265	0.094	0.107	0.066	0.031	0.144
Energy productivity	0.100	0.265	0.094	0.107	0.111	0.031	0.118
Food self-sufficiency	0.100	0.265	0.469	0.321	0.332	0.656	0.357
Crop productivity	0.100	0.088	0.281	0.321	0.047	0.094	0.155
CR = 0.08							**∑ = 1**
Composite WEF nexus index (weighted average)							**0.145**

The CR for the pairwise matrix is 0.08, which is within the acceptable range. The weighted average of all the indices is the composite WEF nexus integrated index. Table 4.6 provides the classification categories for the indicators and the WEF nexus integrated composite index for ranking resource performance as proposed by (Nhamo *et al.*, 2019c).

Table 4.5: WEF nexus indicators performance classification categories

Indicator	Unsustainable	Lowly sustainable	Moderately sustainable	Highly sustainable
Water availability (m^3/per capita)	< 1 700	1 700-6 000	6 001-15 000	> 15 000
Water productivity (US$/$m^3$)	< 10	10-20	21-100	> 100
Food self-sufficiency (% of pop)	> 30	15-29	5-14	< 5
Cereal productivity (kg/ha)	< 500	501-2 000	2 001-4 000	> 4 000
Energy accessibility (% of pop)	< 20	21-50	51-89	90-100
Energy productivity (MJ/GDP)	> 9	6-9	3-5	< 3
WEF nexus composite index	0-09	0.1-0.2	0.3-0.6	0.7-1

Source: Nhamo *et al.* (2019c)

4.3.5 Performance of WEF nexus indicators in southern Africa

Figure 4.5 represents the current performance and status of WEF resources in southern Africa, showing a clear imbalance and uneven resource allocation and distribution.

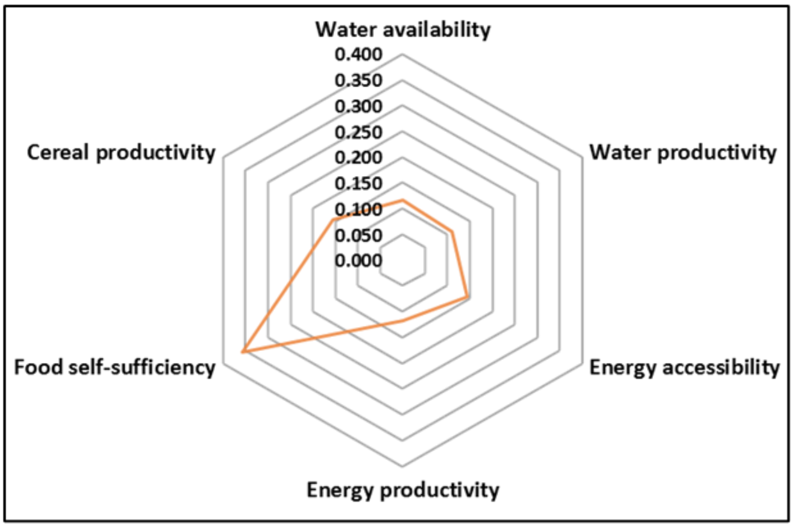

Figure 4.5: Current WEF nexus performance in southern Africa. The deformed amoeba (the orange centrepiece) indicates an imbalanced and unsustainable resource performance resulting from a siloed resource use and management approach. The region should thrive on having a balanced centrepiece, which should be circular.

The lowly sustainable integrated WEF nexus index of 0.145 indicates that resource utilisation and management performance is very low and exacerbates regional vulnerabilities. There is an over-emphasis on food security (food self-sufficiency) at the expense of other sectors. This is mainly due to sectoral approaches in resource management, which do not provide opportunities to minimise trade-offs. Although much effort has been made on food self-sufficiency, showing an index of 0.357, water allocation towards agriculture affects other competing sectors. Most efforts seem to be directed towards agriculture, yet water and hydropower (the main energy source) are in short supply. Thus, Figure 4.5 pinpoints urgent sectors for prioritising interventions.

Except for South Africa, the region depends on hydropower as the main energy source; thus, energy and agriculture compete for scarce water resources (Mabhaudhi *et al.*, 2016). This places the region in a highly vulnerable position because when there is drought, water, energy and food scarcity, as these resources are climate-sensitive, a three-way security threat. This was evident during the 2015/16 El Niño Southern Oscillation (ENSO) induced drought, which caused insecurities of WEF resources

(Nhamo *et al.*, 2019a). The increasing frequency and intensity of recent cyclones are causing immense devastation to agriculture and infrastructure and loss of human life and health (Nhamo *et al.*, 2019a). Still, under such an imbalanced situation, the region intends to increase the irrigated area from 3.5% to 7% of the cultivated area. Whilst increasing irrigated area is a noble idea as it enhances food security to some extent, there is also a need to consider a cross-sectoral approach to avoid transferring challenges to other sectors and achieve a circular shape in the WEF nexus indices in the spider graph (Figure 4.5). The shape of the spider graph indicates priority areas needing immediate intervention.

Under such a scenario, as presented in Figure 4.5, the rural poor normally suffer the brunt of uncoordinated management of resources. Current resource management is unsustainably very low at 0.145. Although the region has improved in agricultural production, as indicated by previous studies (Nhamo *et al.*, 2019d), the region generally fails to meet the food requirements of its growing population and usually relies on international aid to supplement local food deficits (Nhamo *et al.*, 2019a). Therefore, there is a need for a paradigm shift from a sovereignty and silo mindset towards regional integration and cross-sectoral resources management for regional economic development and to improve people's livelihoods. This is supported by the transboundary nature of resources in southern Africa and similar challenges across countries, as climate change does not respect political boundaries (Nhamo *et al.*, 2018).

The WEF nexus analytical tool is important for transforming livelihoods. It identifies priority areas for intervention and ensures that rural areas are not left behind in regional, national and local developmental projects. Prioritising rural development in southern Africa ensures gender and social inclusivity by improving the livelihoods of vulnerable groups such as women, children and the youth who form the majority of rural communities (AUC, 2009; Holmes and Jones, 2011). The results indicate the need for regional planning, coordination and monitoring of resources in southern Africa as resources a generally transboundary (Mpandeli *et al.*, 2018). For southern Africa, in particular, managing resources at a regional level is a catalyst for regional integration and a pathway to improving rural livelihoods and attaining the 2030 agenda on sustainable development.

4.4 Recommendation on improving rural livelihoods in southern Africa

Improving livelihoods, particularly rural livelihoods, depends on implementing a holistic and systematic approach such as the WEF Nexus Analytical Livelihoods Framework. Whilst food and nutrition security are a priority, especially in southern Africa, a WEF nexus approach would mitigate trade-offs and highlight vicious feedback with energy and water. Importantly, the WEF Nexus approach provides a framework for sustaining rural resources whilst maximising the positive synergies and identifies how best to build resilience into rural livelihoods and wellbeing. The following recommendations are proposed for improving resource management and livelihoods of poor rural people in southern Africa in the face of climate change. At the same time, pursuing regional development goals in a manner that integrates across the region that enhances synergies and emergent properties:

- Embracing a cross-sectoral nexus thinking in conceptualising, implementing and evaluating WEF resources planning and management. Specifically, this could be incorporated within a Theory of Change (TOC) model to establish the pathways to understanding the underlying logic, assumptions, influences, causal linkages, and expected outcomes of the WEF nexus analysis in uplifting rural livelihoods and building resilience to climate change.
- Exploit the untapped abundant renewable green energy sources, like wind and solar, to increase energy availability and access, as well as to reduce energy costs and provide clean energy for poor rural people. Solar and wind energy can easily reach the rural population as they can be installed near the demand area, reducing the environmental footprint and the unintended trade-offs and/or consequences for other sectors such as water security or food production.
- Explore conjunctive water use, exploiting untapped groundwater resources for irrigation and domestic use to counter rainfall variability and supplement surface water resources. Currently, 80% of the cultivated area is rainfed, which is at great risk from climate change. Local access to groundwater resources to supplement rainwater would enhance household food and water security.
- A combination of increased access and availability of water, combined with clean energy, would contribute significantly to uplifting the standard of living

(nutrition, health, and well-being) among poor rural people whilst countering the potential negative consequences of climate change on these. This is especially so for public health elements associated with malnutrition, water-borne diseases, and food preparation and heating with wood and paraffin.

- Design and develop cross-sectoral governance structures like climate change policies, strategies and adaptation plans at the regional level. These should be aligned with regional institutions and policies to unlock the WEF nexus approach's potential and effectively exploit the potential of transboundary resources. For example, the Regional Agriculture Policy (RAP) can be linked to Water and Energy Policy. They can inform decision-making on sustainable agricultural expansion and development, reveal trade-offs across sectors, and reduce unintended consequences, especially for downstream users.
- Investments in research, development and innovation promote producing more with fewer resources, reducing waste, and minimising losses for enhanced sustainability. This includes investments in efficient energy technologies to improve energy efficiency and productivity. Secondly, investments in smart and efficient irrigation technologies, including for local groundwater and storage capacity, would contribute to decreasing agricultural surface water use, improved water productivity and access, and resilient household agricultural production. In addition, adopting climate and water-smart agricultural practices could reduce water and energy demand in agriculture.
- Build resilience at the regional level and promote integration through the WEF nexus approach as it identifies opportunities for climate change adaptation and reduction of poverty and vulnerability through coordinated WEF infrastructure development, improved management of transboundary natural resources and maximising regional competitive advantages for agricultural production. This has the potential to improve regional resilience and resource use efficiency. This is particularly relevant for southern Africa as most resources are transboundary and, if not well managed, may cause conflict (Nhamo *et al.*, 2018).
- As the WEF nexus is at the heart of sustainable development, it is also central to regional dialogues on economic development and monitoring the

performance of SDGs. Therefore, adopting the WEF nexus at the regional level promotes sustainable resource utilisation, inclusive economic development, and job creation, thereby improving the livelihoods and well-being of people. The WEF nexus is, thus, a tool capable of assessing and monitoring SDGs implementation and performance, particularly SDGs 2, 3, 6 and 7. For example, there is a strong case for a regional food security initiative as opposed to current national food security strategies, as this would maximise the region's competitive advantages in crop and livestock production whilst maximising household food security and buffering the region against local droughts. This would also encourage new investments in areas lacking any, leading to job creation and creating a virtuous circle for regional integration efforts.

- Link climate change scenario planning with the WEF Nexus Analytical Livelihoods Framework to enhance the reflexivity, resilience, responsiveness and revitalisation of governance and adaptation strategies. Reflexivity is the capability to systematically and continuously deal with a variety of problems as they emerge; resilience is the ability to bounce back to the original basic state of function after a perturbation; responsiveness is the ability to deal with dynamic demands and expectations and; revitalisation is the ability to reignite policies and ensure their continuous application (Breeman *et al.*, 2015). These scenario planning include the Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs), which are a set of pathways and frameworks developed to facilitate integrated analysis of long-term and near-term modelling experiments for climate change to assess vulnerabilities and recommend adaptation and mitigation strategies (van Vuuren *et al.*, 2011; Riahi *et al.*, 2017).

4.5 Conclusions

The development of WEF nexus indicators and composite indices for southern Africa has highlighted the unsustainability of current resource utilisation and management in the region, mainly due to the siloed sectoral approach to resource management. Whilst more emphasis on food self-sufficiency may ensure national food security to some extent, there are risks to rural household food security and wellbeing and transferring problems to other sectors when there is no balance and coordination in resource development and utilisation among sectors. The WEF Nexus Analytical Livelihoods Framework is a catalyst for managing resources and sustainably building resilient rural communities as it indicates priority areas needing immediate intervention. The numerical relationship among the WEF nexus indicators shows unbalanced resource management, increasing risk and vulnerability. The transboundary distribution of resources in southern Africa favours the management of resources at a regional level; this would contribute to the region's developmental targets and to achieving the 2030 Global Agenda on Sustainable Development. The study demonstrates the use and importance of the WEF nexus in providing decision-makers with tools to develop, manage and monitor resource use for sustainable development holistically and systematically. We highlight the potential of the WEF nexus as an inclusive, transparent, intergovernmental approach for all stakeholders, supporting SDGs and promoting the formulation and use of scientifically enabled policies, monitoring, assessment and cooperation. The link between WEF and SDG indicators is an opportunity for further studies on assessing the performance of related SDGs using the WEF nexus analytical model. The tool is important for climate change adaptation strategies and for creating resilient communities through the coordinated resource management framework presented in the study. The analyses highlighted the gap in data availability at the household level. Thus this study focused on regional-level analyses. Future studies should focus on household scale analyses, which will translate to a greater impact. Most critically, our WEF nexus approach emphasises the trade-offs and unintended consequences of the current approaches, with direct negative consequences for poor rural households regarding resource security and wellbeing, while indicating priority areas for intervention.

5 APPLICATION OF THE MODEL AT THE NATIONAL LEVEL FOR ASSESSING PROGRESS TOWARDS THE SDGS

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5.1 Introduction

Natural resources are under pressure to meet the demands of a growing population, yet they are being depleted worldwide (Pimentel, 1991; de Sherbinin *et al.*, 2007). In 2017, over 1.06 billion people, predominantly from rural areas, had no access to safe and affordable energy; half of these people live in sub-Saharan Africa (IEA, 2014). As of 2016, some 793 million people in the world were still undernourished, and 2.4 billion had no access to improved sanitation (FAO/IFAD/UNICEF/WFP/WHO, 2018). Moreover, ecosystems are degrading at an alarming rate, as evidenced by a declining trend in the productivity of a fifth of the Earth's land surface covered by vegetation between 1998 and 2013 (MacDicken, 2015). Significant drivers of the stress on ecosystems include, but are not limited to, increasing demand for food due to rampant population growth and dietary transitions, accelerated economic development, rapid urbanization, environmental modifications, climate variability and change, among others (Avtar *et al.*, 2019). The projected population increase in the human population to about 9 billion people by 2050 would cause a rise of 80% in energy consumption and a 60% increase in food demand (IEA, 2014; FAO/IFAD/UNICEF/WFP/WHO, 2018). The changes may require allocating more freshwater resources to agriculture, a sector already using nearly 70% of available freshwater resources (Pimentel *et al.*, 2004). These environmental and societal changes adversely modify the socio-ecological system, altering wildlife habitat and causing wildlife to move closer to human habitats (Nyhus, 2016). Increasing wildlife-human interactions have seen the emergence of novel infectious disease from wildlife, such as the Ebola (Morse *et al.*, 2012; Allen *et al.*, 2017) and Covid-19 (WHO, 2020).

Resource depletion and degradation, impacts of climate change, the emergence of novel infectious diseases, and socio-economic inequities, among other stresses, resulted in the launching of the 2030 global agenda on sustainable development by 198 countries, members of the United Nations (UN) in 2015, in an attempt to promote sustainability in resource management and ensure a healthy human-environment relationship (UNGA, 2015). The 17 Sustainable Development Goals (SDGs) are a call to action by all countries to promote prosperity while protecting the planet (UNGA, 2015). The Goals are monitored through 169 targets that collectively describe the world's progress towards achieving a sustainable future (UNGA, 2015). The SDGs are designed to recognise the interlinkages between human well-being, economic prosperity and a healthy environment (UNGA, 2015). The recognition of the interlinkages in the challenges in the SDGs context witnessed the prominence of nexus thinking as a lens to address interlinked and cross-cutting challenges holistically (Mabhaudhi *et al.*, 2020). The water-energy-food (WEF) nexus has already emerged as a polycentric approach promoting resource management sustainability (Hoff, 2011). However, other nexuses, including the water-health-environment-nutrition (WHEN) nexus and urban nexus, have since emerged (Liu *et al.*, 2018). The term “nexus planning” was derived from the fact that there are many other nexuses and not only the WEF nexus that has generally been used (Nhamo and Ndlela, 2021).

The term “nexus planning” refers to interconnectedness and interlinkages between sectors, including the synergies and trade-offs related to their management (Nhamo *et al.*, 2018; Nhamo and Ndlela, 2021). Previous studies have summarised these interlinkages as “water for food and food for water, energy for water and water for energy, and food for energy and energy for food” (Foran, 2015; Simpson and Jewitt, 2019). This term emphasises the security and the transferability of challenges from one sector to another and motivates a holistic approach to resource management (Zhang *et al.*, 2018; Nhamo and Ndlela, 2021). The Food and Agriculture Organisation (FAO) defines nexus planning as an analytical tool for quantifying the interactions among linked but distinct sectors (FAO, 2014). Therefore, the concept is three-dimensional as it can be used as a conceptual framework, for discourse or as an analytical tool (Albrecht *et al.*, 2018; Nhamo *et al.*, 2020a). Thus, the essence of nexus planning is the integrated management of interlinked sectors/resources to mitigate trade-offs and maximise synergies that enhance sustainability. In the current study context, nexus planning refers to applying nexus thinking (WEF and WHEN) to inform decision-making.

Nexus planning is a transformative approach in that it differs from previous decision-making approaches that have been considered sector-specific and "siloed" (Liu *et al.*, 2018; Nhamo *et al.*, 2018). This has often resulted in trade-offs, undermining sustainability and meaningful beneficiation. For example, southern Africa's call for irrigation expansion exacerbates water scarcity (Mabhaudhi *et al.*, 2018a). At the same time, such irrigation expansion is impeded by a lack of energy (Nhamo *et al.*, 2018). The analyses by Nhamo *et al.* (2020a) highlighted unsustainability due to an overemphasis on food security without careful coal mining, driven by energy considerations, which threatened food security in Mpumalanga. This province possesses almost 50% of the country's arable land (Simpson *et al.*, 2019). A report by Mabhaudhi *et al.* (2018b) confirmed that conflicts in policies, which were not always integrated, created implementation challenges and threatened sustainable development.

As the post-2015 focus has shifted towards implementing the SDGs and assessing the progress being made towards attaining a sustainable planet by 2030, a significant research challenge is developing tools and models to monitor and evaluate implementation progress by countries and interpret the data related to their monitoring (Lim *et al.*, 2016; Maurice, 2016). Another challenge is aligning national policies and development plans with SDGs to avoid conflicts and policy incoherence (Maurice, 2016; Nabyonga-Orem, 2017). Research and decision-making initiatives have tested methods to effectively monitor and evaluate progress in implementing SDGs and reporting to the global body (Janoušková *et al.*, 2018). The SDGs were developed so that each of the targets is assessed through one or more indicators that keep track of progress towards set targets. The indicators are the backbone of monitoring progress towards sustainable development by 2030, depending on data availability.

Congruence between nexus planning and the SDGs has many advantages, and nexus planning is proposed as a "fitting approach" for integrating and assessing SDGs implementation (Mitra *et al.*, 2020). The essence of nexus planning is to ensure resource security, enhance environmental and human health and achieve sustainability (Liu *et al.*, 2018; Nhamo *et al.*, 2020a). The method simplifies understanding the intricate and systematic interactions between the natural environment and human activities (Mpandeli *et al.*, 2018; Nhamo *et al.*, 2020a). Nexus planning is an apt platform to manage natural resources across sectors, sustainably, and spatial scales, thus relevant to assessing progress towards sustainable development over time.

There is a surge in global recognition of nexus planning's importance in leveraging the SDG implementation process and subsequent monitoring and evaluation, particularly towards making informed decisions on goals, targets, and indicators (Liu *et al.*, 2018; Nhamo *et al.*, 2020a). As a cross-sectoral approach, the WEF nexus supports the integration of indicators across sectors and clarifies how best resources can be allocated between competing needs, making nexus planning the aptest tool to support strategic interventions that lead towards sustainability by 2030 (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo *et al.*, 2021). The method integrates the three intricately related resources and clarifies the complex and dynamic interlinkages between resources, linking them directly to related SDGs. Therefore, this report presents a study demonstrating how nexus planning is used to assess sustainability progress, comparing resource management status in South Africa between 2015 and 2018. We used the approach to evaluate the sustainability of resource management and propose pathways to achieve sustainability by applying the WEF nexus analytical model developed by Nhamo *et al.* (2020a), which was used to develop a WEF Nexus Analytical Livelihoods Framework (ALF). This is achieved through assessing resource utilisation and performance in southern Africa in the context of achieving the 2030 Global Agenda of SDGs, that is, how best to build resilient rural communities and enhance sustainable rural livelihoods. The WEF Nexus ALF is a systems approach that analyses and assesses the interactions between the natural environment and the biosphere, facilitating more coordinated management and monitoring of resources (Nhamo *et al.*, 2018). As the WEF Nexus ALF monitors the performance of resource development, it is also essential for assessing the performance and progress of Sustainable Development Goals (SDGs) that are directly related to the WEF nexus (Goals 2, 3, 6 and 7).

5.2 Materials and methods

5.2.1 A methodological framework to assess progress towards SDGs

Linking nexus planning and SDGs encompasses five thematic themes: (i) description of nexus analytical tool, (ii) defining WEF nexus sustainability indicators, (iii) linking nexus planning and related SDGs indicators, (iv) periodic assessment and monitoring of SDGs performance, and (v) benefits of periodic SDGs monitoring (Figure 5.1). A water-energy-food nexus integrative model was adopted in this study (Nhamo *et al.*, 2020a). The model defines the indicators for a particular nexus under consideration and calculates composite indices to establish an integrated numerical relationship among distinct but interlinked sectors (Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). By establishing the numerical relationships between distinct indicators, the model identifies areas needing immediate intervention to balance resource use and achieve sustainable management. Establishing indices for each indicator at different time intervals provides pathways to assess SDG's progress.

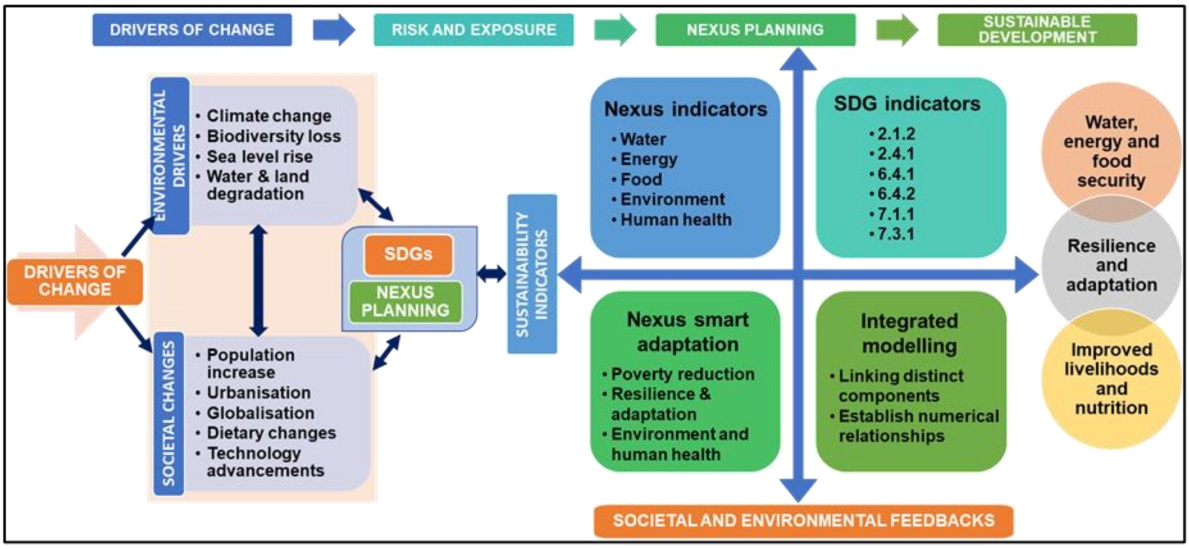

Figure 5.1: Conceptual framework linking nexus processes with Sustainable Development Goals (SDGs)

The rationale is based on establishing quantitative relationships among the intricately connected drivers of change and translating that relationship into meaningful interventions that promote sustainable development. This facilitates understanding how socio-economic, environmental, and ecological interactions influence negative change and, ultimately, unsustainability. The processes unravel societal and environmental outcomes affected by these interactions (food security, ecosystem services and social welfare), which are best explained through sustainability indicators (Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). Nexus modelling is a preferred transformative approach in integrated analyses, using sustainability indicators to provide quantitative relationships among intricately connected sectors and provides pathways towards nexus smart adaptation and sustainable development (Figure 5.1).

Social-ecological systems are complex interactions between human (economic and political trends, population dynamics, changing diets and nutrition, and advances in science and technology) and natural (landcover changes, land and soil degradation, climate change, biodiversity loss, sea-level rise and air pollution) components (Ericksen, 2008; Marshall, 2015). It is paramount to understand these relationships holistically to transition towards sustainable development. Nexus planning connects these interactions by defining, measuring, and modelling progress towards sustainability through indicators formulated around resource utilisation, accessibility, and availability (Nhamo *et al.*, 2020a). Nexus modelling develops knowledge-based tools to assess vulnerability and resilience, promoting interventions that enhance healthy human-environment interactions. The tools facilitate identifying simultaneous resource security and conservation pathways by analysing societal and environmental feedback (social, ecological, political, and economic determinants).

5.2.2 Criteria for selecting nexus planning sustainability indicators

Nexus planning emphasises the integrated management of resources and ensures their security (water, energy, and food) while safeguarding the sustainability of socio-ecological interactions (Fürst *et al.*, 2017; Mahlknecht and González-Bravo, 2018; Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). At the same time, the security of these essential resources and environmental sustainability form the heart of sustainable development (Leck *et al.*, 2015; Scharlemann *et al.*, 2020). These broad linkages between nexus planning and SDGs facilitate an assessment of progress towards the 2030 SDGs (Nhamo *et al.*, 2020a). Therefore, as a transformative approach, nexus planning provides the pathways and tools to assess progress towards sustainable development through sustainability indicators (Mabhaudhi *et al.*, 2019; Mensah, 2019). Sustainability indicators are simplified decision-support tools that facilitate understanding the interrelations among distinct but connected sectors (Warhurst, 2002; Waas *et al.*, 2014). Thus, the essence of indicators is to convert complex relationships into simple numerical expressions that make assessment easier (Warhurst, 2002; Waas *et al.*, 2014).

As the nexus approach is directly related to SDGs in that both are concerned with environmental sustainability and resource security, and the former provides tools to assess progress towards SDGs, the selection of nexus sustainability indicators is, therefore, based on indicators that measure the security of resources as well as promote the sustainability of socio-ecological interactions. Selected nexus indicators are directly linked to the drivers of resource security and environmental sustainability (Nhamo *et al.*, 2020a). Other indicators that could be relevant are included during the assessment as pillars, as proposed by Nhamo *et al.* (2020a). An integrated smart attribute of nexus planning is identifying different interventional priorities to enhance sustainability (Nhamo *et al.*, 2020a). Therefore, the linkages between nexus planning and SDGs are cemented by using indicators to either evaluate implementation progress or establish numerical relationships between distinct sectors/components (Bizikova *et al.*, 2014; Nhamo *et al.*, 2020a).

5.2.3 Linking nexus approaches to related SDGs

As already alluded to, the nexus's value is its documentation of the cross-sectoral and integrated management of resources and simplifying the intricate interlinkages between distinct sectors or components of a system. In this study, the approach is designed to ensure that any planned developments in one sector should only be implemented after considering the impacts (synergies, trade-offs, and implications) in the other sectors (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). As nexus planning sustainability indicators are directly linked to related SDG indicators, it is vital for evaluating SDGs implementation progress (Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). Both nexus planning and SDGs serve the same purpose of ending poverty and achieving economically and environmentally sustainable outcomes. The former serves as an approach to spearhead the implementation of nexus-linked SDGs. Table 5.1 lists nexus planning indicators and the related SDG indicators.

Table 5.1: WEF nexus indicators and pillars and the linked SDG indicators

Nexus type	Sector	Nexus planning indicator	SDG indicator
WEF	Water	The proportion of crops/energy produced per unit of water used The proportion of available freshwater resources per capita	6.4.1 6.4.2
	Energy	The proportion of the population with access to electricity Energy intensity measured in terms of primary energy and GDP	7.1.1 7.3.1
	Food	Prevalence of moderate or severe food insecurity in the population The proportion of sustainable agricultural production per unit area	2.1.2 2.4.1
WHEN	Water	The proportion of the population using safely managed drinking water services The proportion of bodies of water with good ambient water quality	6.1.1 6.3.2
	Human health	Mortality rate attributed to unsafe water, sanitation, and poor hygiene	3.9.2
	Environment	Forest area as a proportion of total land area The proportion of land that is degraded over a total land area	15.1.1 15.3.1
	Nutrition	Prevalence of moderate or severe food insecurity in the population Prevalence of malnutrition	2.1.2 2.2.2

The relationships between SDGs and the two nexus types were established: the water-health-environment-nutrition (WHEN) nexus (Nhamo and Ndlela, 2021) and the water-energy-food (WEF) nexus (Nhamo *et al.*, 2020a). SDG indicators directly linked to WHEN and WEF nexuses indicators (e.g. a direct measure of available water resources, a direct measure of food security, or a direct measure of energy accessibility) are shown in Table 5.1. The focus is on indicators directly falling under the WHEN and WEF nexuses frameworks to ensure water, energy and food security, improve efficiency in resources management to attain sustainability, and ensure human and environmental health (Liu *et al.*, 2018). These nexus planning attributes link the approach to SDGs 2, 3, 6, 7 and 15.

5.2.4 Data sources and availability

Recognizing the importance of the WEF nexus as a decision support tool to assess the progress in implementing SDGs has gathered momentum worldwide; however, data unavailability is the main obstacle to achieving this. Data availability is central in informing and weighting indicators during the PCM process (Nhamo *et al.*, 2019b). Even where data could be available, it usually is heterogeneous (Zuech *et al.*, 2015). Data uniformity is necessary mainly for comparison purposes, particularly across countries (Liu *et al.*, 2017). The variations in data collection and storage bring various challenges, including data disparity, mismatch, and plurality (Liu *et al.*, 2017). Its availability is essential for evaluating trade-offs and synergies and reducing conflicts and vital aspects of sustainable development (Giampietro, 2018). Therefore, data availability is key for establishing indicator weights during the PCM process.

Data at regional and national levels are generally available from open-source databases like FAOSTAT, AQUASTAT, and World Bank Indicators. At the national level, data is also obtainable from national statistical agents. Importantly, where data is not readily available, existing and planned earth observation missions present reliable and long-term data sources (Makapela *et al.*, 2015; Giuliani *et al.*, 2017). For example, the Landsat Mission provides uninterrupted land and atmospheric information backdated from 1972 to date.

The success of sustainable development hinges on reliable data availability at all levels (Lawford, 2019). Publicly available data derived from remote sensing, ground stations or models at any spatial scale is valuable for WEF nexus assessments. Recent advances in sensor technologies and remote sensing methods to collect, analyse and store data have facilitated the quantification and, ultimately, the establishment of numerical interlink-ages between the WEF sectors and assess progress in implementing the SDGs (Estoque, 2020). For example, water use efficiency, crop water productivity, cropped area, and land use change detection can be mapped and calculated using satellite data (Nhamo *et al.*, 2016). The other advantage of remotely sensed data is integrating or fusing data obtained or derived at different spatial and temporal scales or from different satellites (Huang *et al.*, 2018).

5.3 Results and discussion

5.3.1 Overview of WEF and WHEN nexus indicators in South Africa

An overview of both WEF and WHEN nexus indicators for South Africa for 2018 is given in Table 5.2 (WorldBank, 2017). We used the Analytic Hierarchy Process (AHP), a Multi-criteria Decision Making (MCDM) process, to develop relational indices for each indicator (Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021).

Table 5.2: Overview of WEF and WHEN nexus indicators for South Africa

Indicator	Short name	2015	Units
The proportion of the population using safely managed drinking water services	Water accessibility	74	%
The proportion of water bodies with good ambient water quality	Water quality	46.92	%
The proportion of available freshwater resources per capita	Water availability	821.4	m^3
The proportion of crops produced per unit of water used	Water productivity	26.2	$\$/m^3$
The proportion of the population with access to electricity	Energy accessibility	84.4	%
Energy intensity measured in terms of primary energy and GDP	Energy productivity	8.7	MJ/GDP
Prevalence of moderate/severe food insecurity in the population	Food self-sufficiency	6.2	%
The proportion of sustainable agricultural production per unit area	Cereal productivity	5.6	kg/ha
The mortality rate due to unsafe water, sanitation, and lack of hygiene	WASH mortality	13.7 pple	per 100,000 pop
Forest area as a proportion of total land area	Forested area	7.6	%
The proportion of land that is degraded over the total land area	Degraded area	60	%
Prevalence of moderate or severe food insecurity in the population	Food insecurity	52	%
Prevalence of malnutrition	Malnutrition	6.2	%

Source: WorldBank (2017)

The Nexus-SDG linked indicators (Table 5.2) form the basis to assess progress towards sustainability over time. The indicators are related to each other through the AHP, a multi-criteria decision method (MCDM) to establish the numerical relationship, simplify understanding of those intricate relationships, and identify priority areas for intervention (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a). Changes in the relationships between indicators and the progress towards sustainability are best assessed, for example, after every five years when meaningful change is noticeable. Therefore, the AHP can be run at an interval of a five-year period (2015, 2020, 2025 and 2030) to assess progress towards the SDGs.

For South Africa, the period up to 2030 also aligns with the National Development Plan (NDP) – Vision 2030, which outlines the country's development goals and priorities (NPC, 2013). The NDP identifies agriculture as a key sector for job creation and poverty eradication; water and sanitation are linked to improved human wellbeing; energy is crucial to the industrialisation agenda; and human health and wellbeing as a key outcome of sustainable development (NPC, 2013). Thus, the indicators used are relevant to South Africa's planning and priorities.

5.3.2 WEF and WHEN nexuses composite indices for South Africa

Composite indices for the WEF and WHEN nexuses indicators for 2015 for South Africa are given in Table 5.3. The indices are derived through the integrative model developed by (Nhamo *et al.*, 2020a; Nhamo and Ndlela, 2021). The indices are quantitative relationships between the indicators, providing an overview of the state of resources management. The numerical relationship and changes in SDG implementation are best expressed using a spider graph, which illustrates the changes over time (Figure 5.2). As alluded to above, the indices are also useful for identifying priority areas for intervention and guiding the implementation of the NDP. For example, due to historical imbalances caused by apartheid, 19% of people living in rural areas and 33% of the total population lack access to a reliable water supply and basic sanitation services (UNESCO, 2007).

Table 5.3: WEF nexus composite indices for South Africa for the year 2015

Nexus type	Indicator	Composite indices (2015)
WEF	Water availability	0.126
	Water productivity	0.128
	Energy accessibility	0.141
	Energy productivity	0.111
	Food self-sufficiency	0.314
	Cereal productivity	0.180
WHEN	Water accessibility	0.073
	Water quality	0.092
	WASH mortality	0.095
	Forested area	0.155
	Degraded area	0.147
	Food insecurity	0.224
	Malnutrition	0.215

5.3.3 Assessing nexus status and progress towards SDGs

The indicators for the nexus types are presented as spider graphs (Figure 5.2). The WEF and WHEN nexus indicators present deformed relationships between indicators, but the interpretations differ. For the WEF nexus (Fig. 2a), the centrepiece is intended to be circular to indicate a balance in resource management. However, for the WHEN nexus (Fig. 2b), the centrepiece needs to significantly reduce some indicators to improve human and environmental health and reduce the risk of novel infectious diseases. For example, malnutrition and food insecurity indicators need to be reduced drastically, improve water accessibility and quality, rehabilitated degraded lands and increase forested areas to ensure a healthy socio-ecological system.

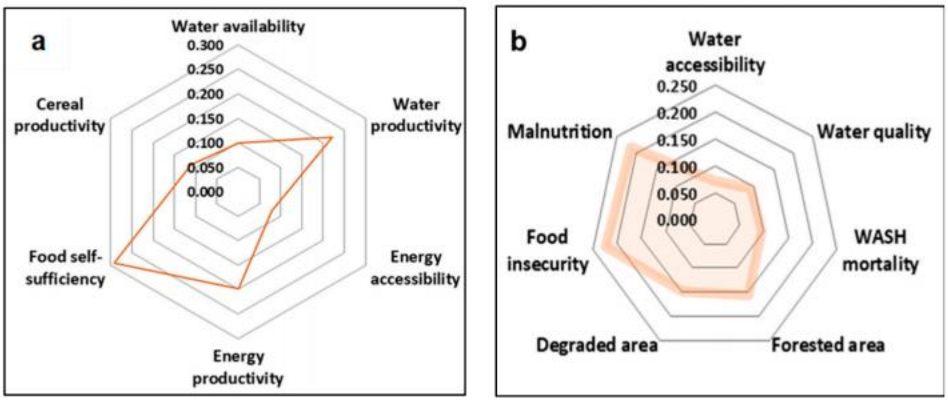

Figure 5.2: Quantitative relationships between the indicators representing the WEF nexus (a) and the WHEN nexus (b) in South Africa in 2015.

The process is repeated for each reference year to assess changes that would have taken place and whether the SDGs' progress is positive or negative. This is exemplified in Figure 5.3, which compares the WEF nexus indicators between 2015 and 2020. In both reference years (2015 and 2020), the country focused more on food security (food self-sufficiency), but in 2020 there was a general improvement in water productivity. However, the progress achieved in some of these indicators is not always regarded as positive, as it could have been achieved at the expense of other sectors. This is true in this case, as some indicators contracted during the same period, as evidenced by the spider graphs' irregular shape. Without compromising food security and the advances in water productivity, interventional processes would inform policy and decision-making to consider allocating more resources to improve the other indicators to achieve sustainable development. A sustainable socio-ecological system is achieved when the centrepieces or the spider graphs become circular, unlike the current status where the graphs remain irregular.

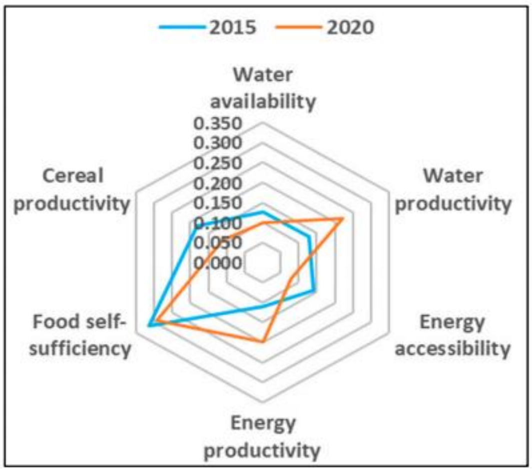

Figure 5.3: Changes in WEF nexus indicators between 2015 and 2018. The comparison is necessary to assess progress towards SDGs.

The results of the WEF and WHEN nexus status and progress broadly indicate the South African context. For the WEF, the results confirm the emphasis on agriculture as a vehicle for addressing poverty, unemployment, inequality, and food security. This has witnessed a significant improvement in investments to increase agricultural productivity in rural areas and increase the area under irrigation. This reflects the southern African context, where food security and sovereignty are policy priorities (Mabhaudhi *et al.*, 2018a). The water-sanitation and health (WASH) challenges continue to persist, despite best efforts to address them; this is because old spatial planning laws continue to impede gridded access to clean and safe water and sanitation in rural, peri-urban, and informal areas. In this regard, off-grid WASH solutions and circular economy approaches are being investigated as alternatives.

5.4 The way forward and recommendations: linking to the SDGs

As already alluded to, balanced and sustainable resource management requires that all indicators attain the highest possible index of the ‘’best’’ performing indicator without compromising other indicators, resulting in a circular shape of the spider graph. Balanced resource management may suggest that resources are being managed holistically to achieve sustainability but can still be classified as unsustainable if the indices remain low. An assessment of the changes in SDGs implementation over time provides the required evidence on integrating strategies to operationalise the WEF nexus to manage resources in an integrated manner from a nexus planning perspective.

The spider graph reveals a country's strengths and weaknesses, indicating priority areas for intervention, making nexus planning a valuable transformative and adaptation decision support tool for integrated resources management. Different scenarios can be developed from the information derived from nexus planning analysis. Thus, nexus planning is essential for tracking resource utilisation and management at a given time. Nexus planning has evolved into a multi-purpose and polycentric decision support tool that simplifies and frames complex interactions between socio-economic and environmental concerns. However, further research is needed on developing scenarios to inform decision-making on balancing resource management and achieving the 2030 global agenda on sustainable development.

However, it should be noted that each nexus type has its dynamics and could be interpreted differently, as shown in the WEF and WHEN nexus types. The essence of nexus planning in sustainable development is its capability to track progress towards SDGs over time and guide decision-making on priority areas for intervention. However, a five-year interval is considered the best interval as it would show significant changes in the implementation of SDGs. Baseline data from national statistical agencies could be the best for this analysis if readily available.

While the case study focused on South Africa, the findings of this study apply to countries in southern Africa, specifically, and the global South, broadly. These countries share a similar history, context, and developmental challenges. Developing nexus planning tools and models facilitates an assessment of resource management and progress towards sustainable development. As the approach has grown into an indispensable decision support tool to achieve sustainability by 2030, the following important highlights need to be noted:

1. Nexus planning offers the potential to monitor progress towards achieving SDG targets. Some nexus indicators used to generate composite indices are quite holistic and may need to be unbundled to translate to specific SDG indicators. For

example, malnutrition is a broad term used to describe a condition where an individual is unhealthy due to under or overconsumption of certain nutrients (Saunders and Smith, 2010; FAO/IFAD/UNICEF/WFP/WHO, 2018). Linking malnutrition data and composite index to SDGs requires a breakdown into different forms of malnutrition (stunting, wasting, overweight, anaemia) as stated in SDG indicators 2.2.1, 2.2.2 and 2.2.3. Breaking down into the different forms of malnutrition defined by the SDG indicators gives a better understanding of nutritional needs and guides countries in prioritizing nutritional interventions. The robustness of the approach is also heavily dependent on the availability of appropriate data directly linked to SDG indicators.

2. Data scarcity at different spatial scales is the major limitation to the success of nexus planning. The more the nexus planning indicator data available, the better it can be linked to SDG indicators resulting in more robust composite indices and sufficient evidence that can be used to prioritize interventions. Also, nexus planning is proposed approximately six years after the SDGs launch, and the SDGs implementation's lifespan is ending by 2030. Given that assessment is recommended at a five-year interval period to show significant changes in SDGs implementation, there is insufficient time to allow enough assessment before SDGs are phased out. A one-time assessment will not be conclusive enough to show the trend of the progress of SDGs implementation.
3. There is a need to upscale the use of nexus planning as a decision tool to leverage the implementation process and progress towards SDGs and subsequent monitoring and evaluation to all southern African countries and at the regional level. A good understanding of SDG indicators and the definition of terms is needed to successfully gather and use appropriate data to link nexus planning indicators to SDG indicators. Platforms for easy accessing and sharing data at regional and national levels from open-source databases, national statistical agencies and remote sensing, ground stations or models would need to be created. Developing protocols and data guidelines accompanied by training may also be beneficial to ensure uniformity and comparable data. The nexus planning approach as a decision tool to assess progress towards development agendas should not just be limited to SDGs. It can be extended beyond 2030 to assess other regional

developmental agendas like the Africa Union Agenda 2063: The Africa We Want and SADC Vision 2050.

5.5 Conclusions

Nexus planning has tracked the intricate linkages between different sectors and has shown progress towards implementing the related SDGs in South Africa. Resource management remains on the lower end of unsustainability, as evidenced by increasing poverty and hunger at the household level, water scarcity, and energy insecurity. The following common principles guide both nexus planning and the SDGs: (a) promotion of sustainable and efficient resource use, (b) access to resources for vulnerable population groups, and (c) maintenance and support of underlying ecosystem services. These linkages have transformed nexus planning into a ‘’fitting approach’’ to assess SDGs implementation over time while promoting the integration of indicators across sectors and reducing the risk of sector-specific SDG actions that usually result in competition between the otherwise related but distinct sectors. The advantage of nexus planning in assessing SDGs' implementation is its capability to analyse trade-offs and synergies between indicators, indicating priority areas for intervention and making it a catalyst to achieve the 2030 global agenda on sustainable development. This can only be achieved if enough data and expertise allow for robust assessments. Nexus planning is a transformative approach that promotes integrated resource planning, a guide in decision-making in the advent of climate change and resource degradation and depletion, a decision support tool for formulating coherent policies and strategies, a governance and management tool for simultaneous water, energy, human health, environment, and food security, as well as job and wealth creation in the long-term. This implies that it is not limited to assessing SDGs but can be extended beyond 2030 to assess other regional developmental agendas like the Africa Union Agenda 2063 and SADC Vision 2050.

6 APPLICATION OF THE MODEL AT LOCAL LEVELS FOR ASSESSING SOCIO-ECONOMIC DEVELOPMENT PLANNING

Luxon Nhamo, Bekithemba Ndlela, Sylvester Mpandeli and Tafadzwanashe Mabhaudhi

6.1 Introduction

Water, energy and food are essential resources that sustain life and livelihoods (Mabhaudhi *et al.*, 2019). The three resources are interlinked and interdependent, so any disturbance in any of the three will affect the other two (Rasul and Sharma, 2016; Nhamo *et al.*, 2018). For example, water and energy are important requirements in food production; energy is also important in water management (extraction, treatment and redistribution); and energy generation needs water (Rasul and Sharma, 2016). This intricate relationship is known as the water-energy-food (WEF) nexus (Albrecht *et al.*, 2018; Nhamo *et al.*, 2018). Nexus planning is based on a systems approach, for example, its use in understanding socio-ecological systems as the primary point of reference in understanding sustainable livelihoods (Rasul and Sharma, 2016). The WEF nexus is just one of the many nexuses suggested in literature; the term "nexus" means seeing and analysing different, but interconnected, components together (Boas *et al.*, 2016; Liu *et al.*, 2018). For example, one of the many nexuses is the atmospheric pollution-climate change-human health nexus. The linkages in the three sectors are evident through atmospheric pollution exacerbating climate change and causing respiratory-related diseases. Thus, addressing climate change alone without attempting to reduce atmospheric pollution does not provide the required sustainable solutions (D'Amato *et al.*, 2016; Manisalidis *et al.*, 2020). As WEF sectors are interlinked, so are the challenges, so much so that focusing on one sector can potentially aggravate and/or transfer stresses to other sectors (UNGA, 2015). This interconnectedness, and the challenges that arise thereof, require systemic and transformative approaches such as circular economy, scenario planning, sustainable food systems and nexus planning to manage trade-offs and synergies and achieve sustainability (Nhamo *et al.*, 2020a).

Early work related to the three-way mutual interlinkages among the WEF sectors emerged in 2008 (Hellegers *et al.*, 2008). The approach then grew in appeal after the World Economic Forum held in 2011, where it was given prominence by the Stockholm Environment Institute (SEI) (Hoff, 2011). Since then, the concept has evolved into an important and transformative approach in sustainability circles, and a search of the term on search engines today yields a vast publication profile. The WEF nexus is increasingly being recognised as a transformative approach that increases resources use efficiencies and informs coherent strategies for sustainable natural resources management (Mabhaudhi *et al.*, 2020; Nhamo *et al.*, 2020a). When applied as a conceptual tool, the WEF nexus provides a framework for understanding the complex interrelations, synergies and trade-offs among water, energy and food (Terrapon-Pfaff *et al.*, 2018). The WEF nexus, when applied as an analytical tool, has evolved into a vital cog in assessing progress towards Sustainable Development Goals (SDGs), particularly Goals 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 7 (affordable and clean energy) and 13 (climate action) (Stephan *et al.*, 2018; Nhamo *et al.*, 2020a). In the current study, we adopt the WEF nexus as an analytical tool for assessing progress towards achieving sustainable livelihoods locally.

Current sector-based approaches to development and service delivery in South Africa influence lower administrative scales, where each sector pursues its strategies and policies (Nhamo *et al.*, 2020a). Given this background, the management of the three sectors in Sakhisizwe Municipality, Eastern Cape Province, South Africa, also falls under sector-specific institutions, with sector-driven mandates derived from the national government setting. Sectoral policies and institutions are formulated to function in silos, an arrangement that inadvertently creates imbalances and often leads to duplication of developmental activities, which often translates to failure due to resource use inefficiencies (Nhamo *et al.*, 2018). In the absence of integration, intentioned sector-based approaches may increase the vulnerability of communities and livelihoods due to continued resource degradation and depletion (Matchaya *et al.*, 2019). Like other growing communities, the challenge of resource insecurities in Sakhisizwe Municipality requires greater cross-sectoral coordination for sustainable service delivery and livelihoods (Tapela, 2012). In this regard, nexus planning can contribute towards informing strategies for sustainable and inclusive socio-economic development, ensuring resource security and improving vulnerable communities' livelihoods (Mabhaudhi *et al.*, 2019).

We, therefore, applied the WEF nexus integrated analytical model (Nhamo *et al.*, 2020a) to understand and quantify the interrelatedness among WEF sectors and develop adaptation strategies for sustainable livelihoods at the local level in Sakhisizwe Local Municipality in the Eastern Cape Province, South Africa. Further to this, we also developed a contextualised municipal nexus framework to inform policy and decision-making at a local level. Applying the WEF nexus locally provides another dimension to the approach's applicability at various scales. Previous work has mostly focused on such household (Hussien *et al.*, 2017), national (Nhamo *et al.*, 2020a), basin (Geressu *et al.*, 2020) and regional (Mabhaudhi *et al.*, 2019) scales. The application at the local level is particularly essential as local government is at the front of service delivery of essential goods and services. Apart from the unique application scale, this study also provides and compares two integrated models for WEF nexus analysis. For South Africa, where service delivery is the mandate of local municipalities, a better understanding of local nexus planning can unlock meaningful opportunities for achieving sustainable livelihoods, poverty alleviation and building resilient communities.

6.2 Materials and methods

6.2.1 Methodological framework

The study's rationale is based on establishing quantitative relationships among the intricately connected, broad and multiple interactions within the water, energy and food resources at a local or community level. Besides simplifying the intricate interactions among these interlinked resources, the analysis provides useful insights for planning, risk identification and mitigation and enhances resilience (Figure 6.1). The aim is to enhance resource availability and accessibility, improve resource productivity at a local level, and attain related SDGs by understanding the socio-economic and environmental interactions. Nexus planning is the main approach to understanding these complex interactions and informing policy on priority interventions that enhance sustainable socio-ecological outcomes (Figure 6.1) (Ericksen, 2008; Nhamo *et al.*, 2020a). Figure 6.1 presents the methodological framework used to achieve these aims, showing pathways towards water, energy and food security, resilience and adaptation, and improved livelihoods and nutrition (Namany *et al.*, 2019b).

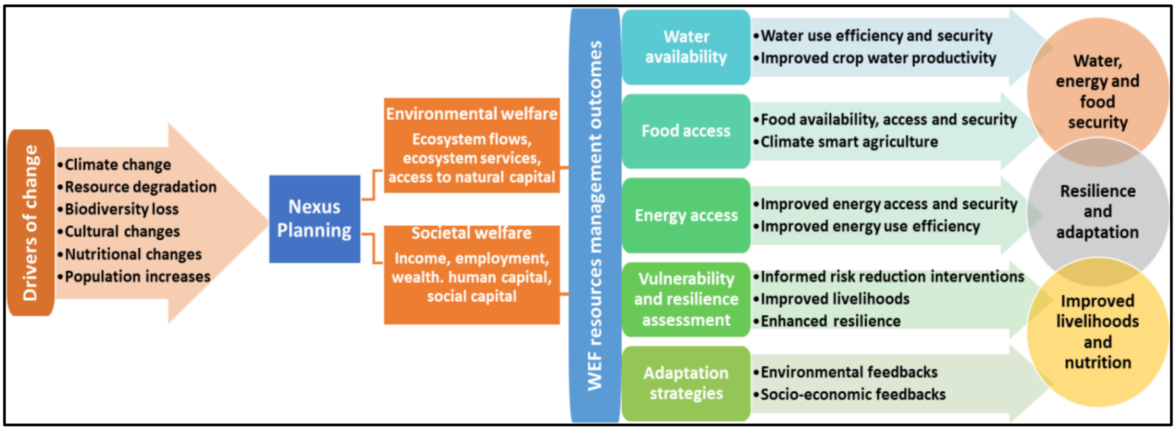

Figure 6.1: A water-energy-food (WEF) nexus methodological framework illustrating the processes and interactions involved in achieving sustainability and resource security at the local/community level.

Therefore, the focus is on (a) the drivers of change, (b) risk and exposure, (c) nexus planning, and (d) resource security. The drivers of change (both socio-economic and environmental) affect resource availability, accessibility and productivity (Misra, 2014) and thus determine community vulnerability and resilience or formulation of adaptation strategies. Knowledge of these interactions is critical for providing transformative pathways towards sustainable socio-economic development. The study is concerned with defining, measuring and modelling progress towards sustainable development through indicators formulated around resource utilisation, accessibility and availability (Nhamo *et al.*, 2020a). The knowledge-based tools provided the WEF resources management outcomes.

6.2.2 Description of the study area

Sakhisizwe Municipality is an administrative area in the Eastern Cape Province, South Africa, located at 26°41′ S, 30°55′ E (Figure 6.2), with an area of 2556 km^2. It comprises gently undulating “table land” forming the Drakensberg foothills, with elevations ranging between 750 m and 2600 m (IDP, 2015). The rocky and undulating landscape makes it difficult for smallholder farmers to be productive and food secure. The highly variable elevation shapes the soil types, where highly erodible clay soils dominate low areas, but the hills in the surrounding areas are made up of strong lithosols (IDP, 2015). It receives an average annual rainfall of between 600 mm and 1000 mm.

The municipality has a diverse and multi-racial population of about 66,097 people, of which 97.7% are black Africans, 1.1% whites, 0.8% coloured and 0.2% Asians (IDP, 2015). The population is largely rural, comprising 61% rural and 39% urban. Most of the rural communities are clustered in the former homeland of the former Transkei area. The land use is, therefore, shaped by a historical setup with vast and fertile lands under commercial farming and the majority in unproductive lands of the former Transkei (van Koppen *et al.*, 2017). Most of the land in the former homeland is unproductive, and the smallholder farmers still use old farming practices that are environmentally unsustainable. As a result of these socioeconomic inequalities, communities residing in the former homelands are persistently vulnerable to climate change impacts. The vegetation is grassland, with scattered shrubs, typical of a savanna land and areas where the black majority settled.

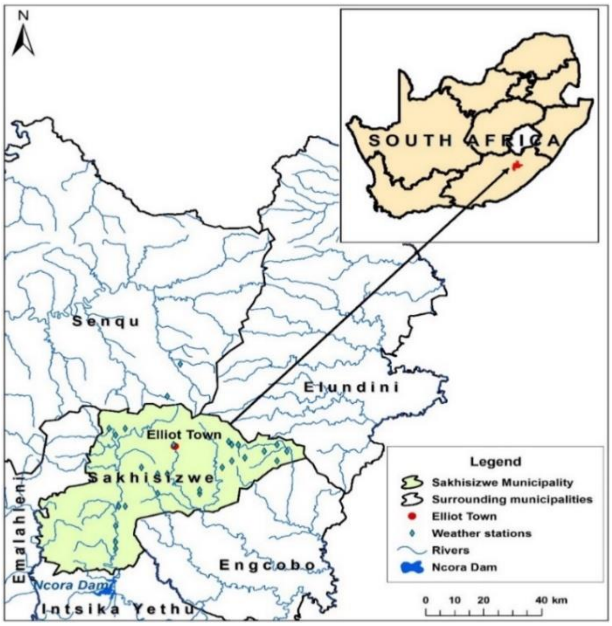

Figure 6.2: Location of Sakhisizwe Municipality in South Africa and surrounding municipalities.

6.2.3 WEF resources endowment in Sakhisizwe Municipality

The municipality's provision of water and sanitation remains a major challenge, as 39% of the population has no access to reliable and clean water, and 51% are without proper sanitation (IDP, 2015). Although agriculture uses the bulk of the freshwater resources, crop production remains very low, often failing to meet the food requirements of a growing population (IDP, 2015). Freshwater is not always guaranteed as most are allocated to commercial farms, and poor agricultural practices contribute to water pollution. Rainfall has been declining due to high climatic variability and change, exacerbating the challenge of water scarcity. Some water sources have gone dry due to drought, and groundwater use has increased.

Consequently, the municipality often undertakes strict water rationing measures, and poor communities often receive water supplies from mobile water tankers. Inequality also manifests in the water sector as commercial farmers have private dams and boreholes (IDP, 2015). This has been the general trend over the past years; the water supply has been diminishing.

Hydroelectricity is the major energy source in the municipality, currently accounting for over 97% of the energy supply, with 79% of households having access to electricity and the remaining 21% relying on gas and biomass (IDP, 2015). A power station at Ncora Dam provides the electricity used for irrigation, but the frequency of droughts has threatened the electricity supply in recent years. However, water transfers have been sustaining water supply and agriculture through inter-basin water transfers by diverting water from nearby river basins to supplement the water shortages (Matchaya *et al.*, 2019). The threat of drought and degrading water resources requires transitioning from hydro-power to other renewable energy sources like solar energy.

Agriculture potential is very high in Sakhisizwe Municipality as it is endowed with vast fertile soils but remains under-utilised (IDP, 2015). Approximately 40% of the land in the municipality is arable. The scattered vegetation and high rainfall make the land susceptible to soil erosion. Rainfed agriculture is predominant among smallholder farmers, and irrigated agriculture is among commercial farmers. Due to the increasing uncertainty in resource availability, the viability and sustainability of rainfed cropping systems are gradually declining. Population growth raises the demand for more space to settle and the demand for food, at the same time reducing the arable land. As the population increases, more land is cleared for new settlements and other economic activities. This is of major concern in a municipality where farming is the major economic activity, providing employment opportunities and a food security anchor.

Sixty-one percent of the population living in rural areas relies on natural systems for their livelihoods, exposing them to climate change risks. Historical imbalances shape resource distribution and access. This highlights why most people in the municipality depend on social grants from the government (StatsSA, 2018). The need to reduce vulnerability to climate risks and provide adaptation strategies to build resiliency and achieve sustainable livelihoods is high in a municipality beset with multiple historical inequalities (Tapela, 2012).

6.2.4 The WEF Nexus-Livelihoods conceptual framework

Livelihoods security, the basis for sustainable development, is determined by socio-ecological interactions driven by population growth, urbanisation, climate change and natural hazards (Kok *et al.*, 2016; Newman *et al.*, 2020). Some evidence of socio-ecological changes manifests through the increased frequency and intensity of extreme weather events and the emergence of novel infectious diseases with origins from wildlife (Jones *et al.*, 2008). These novel socio-ecological interactions are a risk to human health and are increasing the vulnerability of communities to the vagaries of climate change (Bennett *et al.*, 2016). Thus, livelihoods and the environment are intricately interlinked in such a way that any environmental disturbance has a direct impact on livelihoods (Figure 6.3). Addressing socio-ecological challenges, therefore, should consider maintaining food security and universal access to fresh water, as well as access to clean and affordable energy, and promote inclusive economic growth whilst sustaining key environmental systems functionality, particularly in the advent of climatic and environmental changes (Biggs *et al.*, 2015). The close socio-ecological interactions and the intricate interlinkages between livelihoods and the environment suit nexus planning, which integrates distinct components by establishing numerical relationships among those components (Nhamo *et al.*, 2020a). Nexus planning is essential for livelihood analysis as it facilitates sustainable livelihood development.

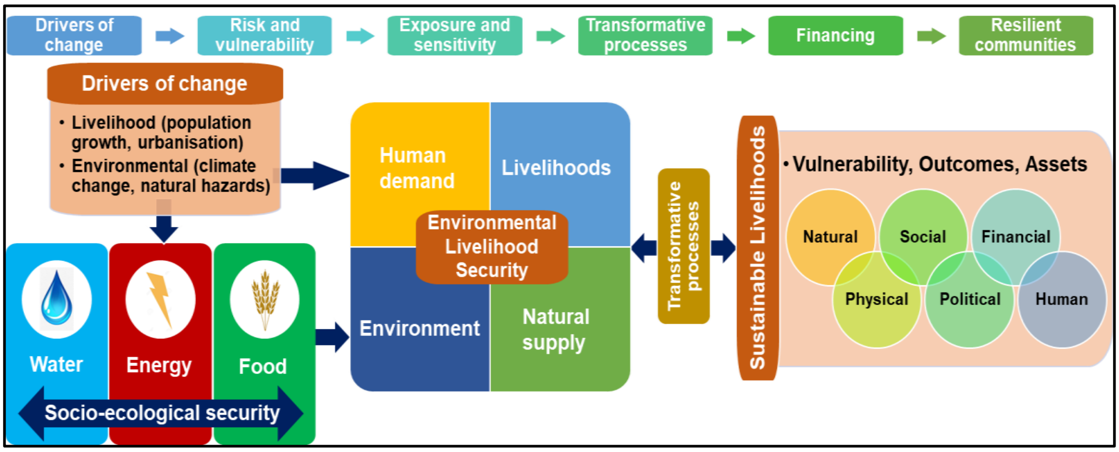

Figure 6.3: The WEF nexus framework for building resilient communities at a local level, integrating the drivers of change with the elements of sustainable livelihoods to attain a sustainable balance between natural supply and human and environmental demands.

To comprehend socio-ecological interactions in the context of sustainable livelihoods and nexus planning, we identified six thematic areas based on a literature search, which include (a) drivers of change, (b) risk and vulnerability, (c) exposure and sensitivity, (d) transformative processes, (e) financing, and (f) resilient communities (Reed *et al.*, 2013; Biggs *et al.*, 2015). The thematic areas are identified as the main drivers towards sustainable livelihoods and are the basis for developing the WEF nexus-livelihoods conceptual framework (Figure 6.3). The WEF nexus-livelihoods conceptual framework illustrates the pathways towards sustainable livelihoods and healthy environments capable of supplying human needs at all times (Mabhaudhi *et al.*, 2019). Sustainable livelihood is achieved when a balance between human demands and natural supply from the environment is attained without compromising the environment's health (Rasul and Sharma, 2016). The delicate and intricate socio-ecological relationship is reinforced by environmental security and livelihood security (Mensah, 2019). Thus, sustainable development and livelihoods are at the centre of the socio-ecological interactions and were the basis for the formulation of SDGs (UNGA, 2015).

Socio-ecological systems are, therefore, well linked not only to the WEF nexus but also to other transformative approaches such as the circular economy and sustainable food systems, which both form an integral part of a sustainable environment and are designed to ensure the most efficient use and management of resources (Jurgilevich *et al.*, 2016). Efficient use and management of resources through informed strategies from transformative processes lead to sustainable livelihoods, which determine the vulnerability, outcomes and assets of a community, which in turn are determined by the natural, physical, social, political, human and financial aspects of society (Reed *et al.*, 2013).

Thus, sustainable livelihoods are based on comprehending available options to access assets that typically include natural, human, social, physical and financial capital (Figure 6.3). In the context of livelihoods, and particularly at a local level, access to assets is analysed through (a) climate change, population dynamics, history and macro-economic conditions, (b) institutional and social processes that include institutions and land tenure, and (c) the livelihood strategies that are used, which include combinations of activities people practice to achieve their livelihood goals

(Krantz, 2001; Nhamo and Pius, 2012). This knowledge facilitates informed interventions to improve livelihoods based on understanding existing coping strategies designed to protect and enhance resilience and the factors influencing them (Nhamo and Pius, 2012). The approach is suitable for Sakhisizwe Municipality, which is administratively a local area, is based on the WEF nexus-livelihoods framework (Figure 6.2), and aims to provide sustainable pathways towards sustainable human-environment interactions in the municipality and build resilient communities and achieve related SDGs.

6.2.5 Mathematical representation of distinct components of a system

There are two main methods to establish quantitative relationships among different but interlinked components of a system through nexus modelling that are suggested in the literature: (a) differential equations and (b) multi-criteria decision method (MCDM). Both methods were experimented with in the context of the WEF nexus to integrate sustainability indicators representing the securities of water, energy and food, which represent the WEF nexus (Nhamo *et al.*, 2020a). WEF nexus analytical modelling unpacks the complex interlinkages and dynamics among sectors and mathematically represents those dynamics between the inputs and outputs within a livelihoods-environment system. The main outcomes of a socio-ecological system include sustainable livelihoods and healthy ecosystems (Connell, 2010). The numerical representation facilitates classifying a system as sustainable or unsustainable (Nhamo *et al.*, 2020a). The outcomes are dependent on the balance between human demands and natural supply. WEF nexus sustainability indicators (Table 6.1) are the basis for establishing the numerical relationships among the interlinked WEF sectors related to the livelihoods-environment system (Nhamo *et al.*, 2020a).

Table 6.1: Sustainability indicators and quantifying WEF nexus interactions.

WEF Sector	Indicator	Units
Water	The proportion of available freshwater resources per capita (availability)	m^3/capita
	The proportion of crops produced per unit of water used (productivity)	\$/m^3
Energy	The proportion of the population with access to electricity (accessibility)	%
	Energy intensity measured in terms of primary energy and GDP (productivity)	MJ/GDP
Food	Prevalence of food insecurity in the population (self-sufficiency)	%
	The proportion of sustainable agricultural production per unit area (cereals)	kg/ha

Source: Nhamo *et al.* (2020a).

Of the two methods, MCDM and differential equations, the MCDM was preferred as it provides indices for each indicator, which can be shown on a spider graph to give an overview of resource management. Yet, the differential equation produces a single composite index that may not indicate priority areas for intervention (Nhamo *et al.*, 2020a). However, the choice of the method depends on the objective of the work being done. In this study, we aim to provide an integrated relationship between different components of the same system.

6.2.5.1 Integration through differential equations

The state of variables (x) of a system provides the least information necessary to define the state of a system at a given time. A quantitative relationship of variables (x), together with the information on the same variables at an original time (t_0) and the inputs of the system for time (t), indicates data to estimate future system changes and outputs for all time (t) (Åström and Murray, 2010). Outcomes (y) are functions for characterising the input-output relationships. Thus, one way to represent the processes taking place in a system is through differential equations (with time being the independent variable). These transitional equations are formulated in a state-space form that has a certain matrix structure and is commonly expressed as (Rowell, 2002; Allen and Prosperi, 2016):

$$y_t = h(x_t, u_t, e_t) \quad (6.1)$$

where *y* are outcomes, and *h* is a vector function with *n* components for the *n* outputs *y* of interest. The variables are dependent on time *t*. The equation is a transitional function as it models the current state of a system into its future state (Rowell, 2002). In vector representation, the differential equation is expressed as:

$$\ddot{x} = \frac{dy}{dt} = f\left(x_{t,} u_t, e_t\right), \quad (6.2)$$

where (*f*) is a vector function. The status of a system at any given (*t*) represents a point in an *m*-dimensional state-space, and the dynamic state response x_t is a trajectory traced out in the state-space (Rowell, 2002).

In addition to the differential Equations (6.1) and (6.2), other Equations (6.3) and (6.4) are essential for accounting for feedback to the inputs (Åström and Murray, 2010). The main parameter estimation challenge is data availability at a given spatial scale. However, some data can be modelled from remote sensing or obtained from open data sources like the World Bank Indicators and AQUASTAT.

$$\ddot{e} = \frac{de}{dt} = (x_t, u_t, e_t) \quad (6.3)$$

$$= \frac{du}{dt} = \emptyset(x_t, e_t) \quad (6.4)$$

6.2.5.2 The multi-criteria decision method (MCDM) to integrate WEF nexus sectors

An alternative method is the Analytic Hierarchy Process (AHP), an MCDM tool for structuring and solving complex decisions and planning problems that involve multiple criteria (Kumar *et al.*, 2017). The MCDM facilitates the calculation of integrated composite indices between distinct but interrelated components using a pairwise comparison matrix (PCM). The MCDM is a cross-sectoral planning tool to overcome the increasing demand for essential resources with a vision of sustainable development (Siksnelyte *et al.*, 2018). The sustainability indicators (Table 6.1) are useful for conveying information on the state of a system through composite indices represented through a spider graph. They indicate areas of priority intervention to reduce risk and vulnerability.

The AHP was critical for integrating WEF nexus sectors. It was used to derive ratio scales from discrete and continuous paired comparisons to help decision-makers set priorities and make the best decisions (Saaty, 1977; Saaty, 1987; Triantaphyllou and Mann, 1995). As already alluded, the AHP provides a comparison matrix that allows comparing two indicators simultaneously using Saaty's scale, which ranges between 1/9 and 9 (Saaty, 1977). The process calculates the indices for the indicators through matrix *A* for the priority ranking. The priority ranking is set to the right of the PCM vector *w* of the comparison matrix *A*. Therefore, the method is to calculate the maximum value λ and its corresponding vector *w* such that (Saaty, 1990; Stewart and Thomas, 2006):

$$Aw = \lambda w \tag{6.5}$$

The matrix, A, of n criteria, is determined using Saaty's scaling ratios in the order (n × n) (Rao *et al.*, 1991). A is a matrix with elements aij. The matrix is reciprocal and is expressed as:

$$a_{ij} = \frac{1}{a_{ij}} \tag{6.6}$$

Once the matrix is generated, it is normalised as a matrix *B* with elements b_{ij} and expressed as:

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1} n \ a_{ij}} \tag{6.7}$$

Each weight value w_i is computed as:

$$w_i = \frac{\sum_{j=1} n \, b_{ij}}{\sum_{i=1} n \, \sum_{j=1} n \, b_{ij}}, i, j = 1,2,3 \ldots, n \tag{6.8}$$

The integrated composite index is then expressed as the weighted average of the indices and is an indicator of the general performance of resource management within a system.

Consistency is an important component of a PCM, and an acceptable consistency ratio (*CR*) of less than 0.1 or 10% is always recommended (Alonso and Lamata, 2006). The *CR* is expressed as (Teknomo, 2006):

$$CR = \frac{CI}{RI} \tag{6.9}$$

where: *CI* refers to the consistency index, and *RI* is the random index (Saaty, 1977). *CI* is calculated as:

$$CI = \gamma - \frac{n}{n-1} \quad (6.10$$

where: γ represents the main eigenvalue, and n refers to the number of criteria or sub-criteria in each PCM.

6.2.6 Modelling vulnerability and resilience

Vulnerability can be assessed through large-scale computer simulations at a local scale (Broeck *et al.*, 2011). Such an assessment is essential to better understand resilience from past knowledge of exposure and responses to shocks and stressors to identify areas for current and future policy support (Patel *et al.*, 2017). Trajectory analyses are essential for formulating policies that enhance resilience as they offer insights into temporal livelihoods-environment interactions that consider both past and future conditions, as the present state is defined by the legacy of the past (Stringer *et al.*, 2014). Resilience is needed where there is vulnerability, for where there is a need for resilience, there is some degree of vulnerability (Miller *et al.*, 2010). Human vulnerability and resilience to socio-ecological changes are adversely influenced and affected by changes in the physical, natural, social, political, human and financial set-up (Figure 6.1).

Vulnerability and resilience are composed of exposure, sensitivity and resilience (Miller *et al.*, 2010). Thus, vulnerability (*V*) is a function of the components' recovery potential (*RP*) and potential impacts (*PI*), which are expressed through exposure (*E*) and sensitivity (*S*) (Allen and Prosperi, 2016):

$$V = f(PI, PR), with\ PI = f(E, S) \quad (6.11$$

Outlining vulnerability and resilience is important to illustrate different elements of a system, including establishing numerical relationships and calculating composite indices. The method is an alternative approach to assessing risk and exposure and formulating strategies to build resilience and achieve sustainable livelihoods.

6.3 Results and discussion

6.3.1 Integrating WEF nexus sectors

The WEF nexus-based PCM for Sakhisizwe Municipality is presented in Table 6.2. The diagonal numbers are values of unity (i.e. when an indicator is compared with itself, the relationship is always 1). Because the PCM is symmetrical, only the upper triangle (yellow-shaded) is determined, and the lower triangle represents the reciprocals. As already alluded to, the matrices are established using a scale between 1/9 and 9 (1/9 is the lowest and most insignificant relationship, and 9 is the highest and most important relationship). Due to a lack of data at a local level, the PCM was developed based on expert advice and general knowledge of the municipality (Saaty, 1977).

Table 6.2: Pairwise comparison matrix for WEF nexus indicators in Sakhisizwe Municipality.

Indicator	Pairwise Comparison Matrix					
	Water Availability	**Water Productivity**	**Energy Accessibility**	**Energy Productivity**	**Food Self-Sufficiency**	**Cereal Productivity**
Water availability	1	1/3	1	1/7	1/6	1
Water productivity	3	1	3	5	1	1
Energy accessibility	1	1/3	1	1/2	1/3	1/5
Energy productivity	7	1/5	2	1	3	5
Food self-sufficiency	6	1	3	1/3	1	7
Cereal productivity	1	1	5	1/5	1/7	1

6.3.1.1 Normalised pairwise comparison matrix for WEF nexus indicators

The normalised matrix (resulting using Equations (6.7) and (6.8)) is given in Table 6.3. A *CR* of 0.09 is acceptable, and the weighted average, which is the integrated index, is classified according to the categories given in Table 6.4.

Table 6.3: Normalised pairwise comparison matrix and composite indices.

Indicator	Normalised Pairwise Comparison Matrix						
	Water Availability	**Water Productivity**	**Energy Accessibility**	**Energy Productivity**	**Food Self-Sufficiency**	**Crop Productivity**	**Indices**
Water availability	0.053	0.086	0.067	0.020	0.030	0.066	0.053
Water productivity	0.158	0.259	0.200	0.697	0.177	0.066	0.259
Energy accessibility	0.053	0.086	0.067	0.070	0.059	0.013	0.058
Energy productivity	0.368	0.052	0.133	0.139	0.532	0.329	0.259
Food self-sufficiency	0.316	0.259	0.200	0.046	0.177	0.461	0.243
Crop productivity	0.053	0.259	0.333	0.028	0.025	0.066	0.127
CR = 0.09							∑ = 1
Composite WEF nexus index (weighted average)							0.185

Table 6.4: WEF nexus indicators performance classification categories.

Indicator	Unsustainable	Marginally Sustainable	Moderately Sustainable	Highly Sustainable
WEF nexus composite index	0-0.09	0.1-0.2	0.3-0.6	0.7-1

Source: Nhamo *et al.* (2020a).

To calculate the weighted average, the indices are ranked according to their weight, the highest being 6 and the lowest ranked 1. The composite index for Sakhisizwe Municipality is 0.185, which classifies the municipality as marginally sustainable. The indices vary between 0 and 1, where 0 represents unsustainable resource management, and 1 represents highly sustainable resource management (Table 6.4).

6.3.1.2 Classification categories for indicators and the WEF nexus integrated index

The classification categories (Table 6.4) represent resource management levels, which are essential for determining the intensity or importance of an indicator (Nhamo *et al.*, 2020a).

6.3.2 Interpretation of the Indices

The calculated WEF nexus indices are presented as a spider graph (Figure 6.4) to give a general overview of the numerical relationship of the indicators in a simplified manner. The graph provides the interactions and interdependences of the WEF sectors as seen together, giving an integrated synopsis of the status of resources in the context of use and management. The deformed shape of the centrepiece (Figure 6.4) is an indication of imbalanced resource management. The further an index is from the centre of the axis of the spider graph, the better the level of sustainable development, and the closest to the axis signifies unsustainable development. The representation of the indices numerically unbundles the complex interlinkages between WEF sectors.

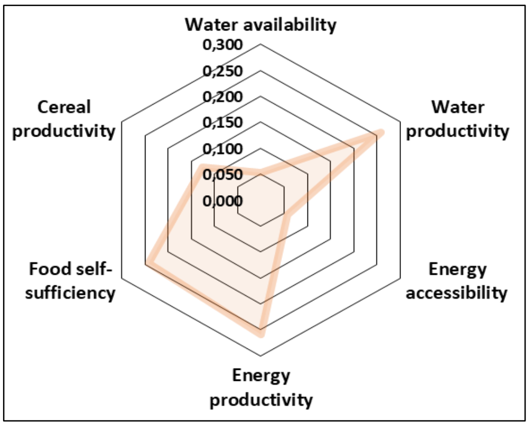

Figure 6.4: Resource performance in Sakhisizwe Municipality in 2018.

There is better water and energy productivity (both at 0.259) in Sakhisizwe Municipality, followed by food self-sufficiency (0.243). The better water productivity in the municipality could be motivated by limited water resources or low water availability (0,053), which often results in water being used sparingly and efficiently. This is a general trend in South Africa as the country is water-scarce (Nhamo *et al.*, 2020a). Although energy production is high, accessibility is still very low at 0.058, as 21% of the population has no access to electricity. The situation is worsened by depleting water resources due to drought and compromises hydroelectricity generation, which is the main source of energy (IDP, 2015). The effects of drought also highlight low water availability in the municipality, which affects energy accessibility and cereal productivity. Water management is an area that needs improvement in the municipality to ensure water, energy and food security, as 61% of the population lives in rural areas and is highly vulnerable to climate change impacts (IDP, 2015). An integrated composite index of 0.185 classifies the municipality into a marginally sustainable category.

6.4 Way forward

The challenges currently facing humankind are systemic, complex and interlinked, whereby emerging stress in one sector only exacerbates the stresses in other related sectors (Birkel *et al.*, 2019). This interconnectedness and the need to achieve sustainability have reignited the importance and use of integrated and systemic approaches in achieving national and global goals anchored on sustainable development (Burch *et al.*, 2019). The importance of transformative and integrated approaches has increased the prominence of the WEF nexus in recent years to address existing complex problems (Mabhaudhi *et al.*, 2020). For example, the COVID-19 pandemic started as a health challenge; however, the subsequent lockdowns triggered a chain of other challenges, such as company closures, unemployment and disruptions in the global demand and supply chain, among other challenges (WHO, 2020). Thus, sector-based or system-specific resilience initiatives such as health systems are usually accompanied with systemic risks, which originate from strategies that lead to suboptimal efficiencies in that targeted sector at the expense of other sectors (Hanefeld *et al.*, 2018; Nhamo *et al.*, 2018; WHO, 2020). As a result of the risks associated with sector-based approaches, there has been an emergence of other nexuses, apart from the WEF nexus, such as the water-energy-food-environment (WEFE) nexus, water-unemployment-migration (WEM) nexus, water-health-environment-nutrition (WHEN) nexus and the rural-urban nexus, among others (Lehmann, 2018; Liu *et al.*, 2018; Landauer *et al.*, 2019). This underlines the urgency to address intricate trade-offs between interlinked sectors in an integrated manner and highlights the importance of transformative approaches in addressing the systemic and interlinked shocks and informing policy on formulating coherent policies and strategies (UNEP and ILRI, 2020).

While nexus planning was initially meant to address global challenges and achieve sustainability at a global level, it is at a local scale (household and community) and natural scale (catchment) where nexus issues are most evident and where adaptation and resilience-building processes should take place (McGrane *et al.*, 2019; Mpandeli *et al.*, 2019) but cascade from these local scales to natural spatial scales (catchments) and jurisdictional scales (political units such as cities, municipalities or provinces). It is at a jurisdictional scale where policies and governance structures that affect households and communities are formulated and implemented (Termeer *et al.*, 2010; Landauer *et al.*, 2019). The temporal scale is equally critical in nexus planning as it is essential in scenario planning (an important component of nexus planning) and for interpreting future climatic and environmental changes, resource availability or population projections at different time intervals (Bhave *et al.*, 2018). Each spatial scale has its dynamics, particularly regarding data availability (da Silva and Hussein, 2019).

Besides the envisaged importance of nexus planning, the approach has had its share of criticisms, particularly for the lack of procedures to turn the approach into an operational framework (Albrecht *et al.*, 2018). Others have even branded it as a repackaging of the Integrated Water Resources Management (IWRM) (Allouche *et al.*, 2014; Benson *et al.*, 2015). Only recently have analytical models been developed to provide practical applicability in a real-life situation and guide policy and decision-making in formulating informed strategies that lead to sustainable development

(Nhamo *et al.*, 2020a). The WEF nexus analytical model has been successfully applied in southern Africa to transform rural livelihoods and in South Africa for assessing resource use and management to inform policy on priority areas for intervention and study applies the approach at the local/community level (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020a). The model is in its early stage of application, and there is still room for improvement.

One critical limitation of the model is achieving consistency with more than nine indicators. Future research is needed to develop scenarios that inform policy and decision-making on achieving a circular shape of the spider graph and attaining sustainable development.

Adaptation strategies to ensure sustainable livelihood-environmental security

Comprehending socio-ecological complexities is essential for formulating informed adaptive responses that ensure sustainable livelihoods and healthy environments. Nexus planning is best suited for assessing polycentric and complex systems like socio-ecological interactions as it simplifies the interlinkages by providing numerical relationships among the diverse but connected components. As already alluded to, the deformed shape of the centrepiece of the spider graph (Figure 6.4) indicates an imbalance in resource management. A balanced and sustainable resource management is attained when the centrepiece of the spider graph achieves a circular shape. The circular shape is best when all the indicators reach the highest possible index. In the case of Sakhisizwe Municipality, this is achieved when the other indicators attain the value of the best-managed indicators, water productivity and energy productivity (0.259). Thus, nexus planning informs policy and decision-making on interventional strategies to prioritise developmental initiatives. The approach is also a platform for stakeholder engagement to harmonise strategies and policies, besides being an analytical, conceptual and discourse framework (Nhamo *et al.*, 2020a). Current sectoral approaches only exacerbate current challenges associated with climate change and increase the vulnerability of communities.

Achieving a circular shape at 0.259 for all the indicators would achieve balanced resource management and assist the municipality in achieving a moderately sustainable category (Table 6.4). A circular shape is, therefore, an indicator of a well-managed resource base. The WEF nexus analytical model allows decision-makers to integrate strategies and policies that increase resource use efficiency. The WEF nexus analytical model is, thus, a decision support tool for monitoring resource utilisation, management and performance, as it captures the interactions among the sectors. It is essential for setting developmental targets and achieving the goals stipulated in the Integrated Development Plan (IDP), National Development Plan (NDP) and relevant SDGs. For policy and decision-makers, the model provides tools to:

- establish quantitative relationships and simplify the intricate interlinkages between water, energy and food resources with livelihoods security;
- identify trade-offs and synergies within a socio-ecological system and formulate informed strategies to achieve sustainable livelihoods and build resilience;
- guarantee the required balance between human demands and the supply of natural resources to achieve livelihoods sustainability;
- plan timely interventions on priority areas and reduce pressures and stresses on a system;
- monitor progress towards a sustainable socio-ecological system; and
- inform transformative solutions to complex socio-ecological systems from a nexus planning perspective.

6.5 Conclusions

We developed a conceptual framework to illustrate the interlinked socio-ecological components and establish the quantitative relationships of those components. This facilitated an understanding of socio-ecological connections and sustainable livelihoods-environment co-benefits at a local scale. This was essential to developing coherent adaptive strategies to alleviate poverty, a central goal of sustainable livelihoods. Assessing the relationship between sustainable livelihoods and environmental outcomes through nexus planning is useful for developing context-specific transformative pathways at a local level. WEF resource securities are key to reducing poverty as they ensure sustainable and equitable resource availability and access. Concurrently, preserving ecosystems is vital for sustaining healthy natural environments and maintaining the ecosystem services they provide, directly or indirectly providing foundations for livelihoods in rural resource-poor communities. The applicability of the WEF nexus integrative analytical model at a local level highlights the applicability of the WEF nexus approach at various scales, especially localised scales that are important for informing human outcomes.

7 DEVELOPMENT OF WEF NEXUS SCENARIOS FOR ASSESSING WEF NEXUS PERFORMANCE AT THE REGIONAL LEVEL

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7.1 Introduction

Studies for ecosystems, natural resources, and their linkages have become imperative for informing decisions and policies on the importance of and responding to global and local environmental and sustainability challenges (van Vuuren *et al.*, 2012; Cilliers *et al.*, 2013; Beach and Clark, 2015; Bretschger and Pittel, 2020). Integral to such studies is exploring alternative futures since today's actions, and short-term decisions potentially have long-lasting and residual effects (Cremades *et al.*, 2019). Tools for imagining the future evolution of systems include traditional planning techniques (forecasting, prediction) and scenario planning. The former techniques use past experiences, current events/trends, knowledge and observation to extrapolate and produce quantitative single-point forecasts for controllable and reproducible systems (Enzmann *et al.*, 2011; Abuzaid, 2018; Bruaset and Sægrov, 2018). However, these attributes are inapplicable to natural resource and environmental systems, which are inherently complex, nonlinear, uncertain, rapidly evolving, and have limited knowledge (Cilliers *et al.*, 2013; Beach and Clark, 2015; Bretschger and Pittel, 2020). Fortunately, scenario planning can be used to characterize the evolution of natural systems (Garmestani, 2014). Unlike prediction that focuses on the most likely single-point change, which it often misses leading to failure from surprise, scenario planning assesses pathways with plausible descriptions of how the future might evolve based on a coherent and internally consistent set of assumptions about the key relationships and driving forces (Rounsevell and Metzger, 2010; Enzmann *et al.*, 2011; Schoemaker, 2016). According to (Keskinen *et al.*, 2015; Hoolohan *et al.*, 2018; Uden *et al.*, 2018), scenario planning involves considering the alternative, plausible futures in situations with high uncertainty and complexity and a low level of control over a focal variable or system. Scenarios are combinations of pathways of the possible future state of the world, while pathways are plausible trajectories of future conditions that describe a single component, such as Representative Agricultural Pathways (RAPs) for the evolution of agricultural systems (Valdivia *et al.*, 2015), Shared Socioeconomic Pathways (SSPs) for changes in socioeconomic conditions (O'Neill *et al.*, 2014), and Representative Concentration Pathways (RCPs) climate change (van Vuuren *et al.*, 2011; Antle *et al.*, 2017a). According to Dean (2019), scenario planning addresses more explicitly for complexity and uncertainty of the environment, not to accurately predict the future but rather to highlight different possible futures for informing policy-makers of new potential trends, key factors/drivers and actors that may alter the status quo, and the associated opportunities and threats for each alternative future condition (Moss *et al.*, 2010; Keskinen *et al.*, 2015; Star *et al.*, 2016; Palazzo *et al.*, 2017; Antle and Valdivia, 2021).

Scenario planning facilitates innovative and robust solutions to complex problems and uncertain futures through learning towards transformational change, coping with uncertainty, mutual understanding of alternative future evolution, identifying thresholds in the system, and crafting strategies to better adapt to changing conditions (Peterson *et al.*, 2003; Hoolohan *et al.*, 2019; Gerlak *et al.*, 2021; Naidoo *et al.*, 2021). Notable applications of scenarios in the last two to three decades were done by the Intergovernmental Panel on Climate Change (IPCC), Millennium Ecosystem Assessment (MEA), United Nations Environment Programme (UNEP), International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), Organisation for Economic Co-operation and Development (OECD), International Energy Agency (IEA), and Food and Agriculture Organization of the United Nations (FAO) (Alcamo, 2008; van Vuuren *et al.*, 2012; Kishita *et al.*, 2016). Under the existences and mandates of these organizations, maybe, a majority of these scenarios and pathways were more focused on specific individual sectors or disciplines such as climate change (causes, impacts), environment, ecosystem, agriculture, water, and energy. By IPCC, for example, the previous pathways and scenarios include First Scientific Assessment 1990 (SA90), the six IPCC Scenarios 1992 (IS92), the forty Special Report on Emissions Scenarios (SRES), the five CMIP5 SSPs and four RCPs (2010, 2014), and the eight/nine CMIP6 SSP-RCPs (2016)

(Nakicenovic *et al.*, 2000; Girod *et al.*, 2009; van Vuuren *et al.*, 2011; O'Neill *et al.*, 2014; O'Neill *et al.*, 2016; Gidden *et al.*, 2019).

Water and the related energy and food systems are uncertain since their supply and demand are affected by complex climate, ecological, social, economic, and institutional dynamics (Hoolohan *et al.*, 2018; Gerlak *et al.*, 2021). These and other drivers complicate society's ability to ensure sustainable security of water, energy, and food for social sustenance and economic development in a degrading environment (Mabhaudhi *et al.*, 2016; UN-Water, 2018; Yang *et al.*, 2018). Currently and according to (Sivakumar, 2021), (i) agriculture consumes about 70% of global water, (ii) energy production consumes about 75% of all industrial water withdrawals, (iii) food production and supply chain accounts consume about 30% of global energy; and (iv) about 90% of global power generation is water-intensive. The business-as-usual future projections for 2030 and 2050 relative to 2012 predict demand increases of 40-100% for energy and 50-70% for food, which will require 20-55% more water and 10-30% more agricultural land (WEC, 2013; IRENA, 2015; FAO, 2022; UNESCO, 2022). Although the scenario space is wide and uncertain, they all point to the need for increased production of food and generation of energy to meet the demands, which will potentially further escalate environmental and sustainability challenges, degradation and depletion of natural resources, and climate change (CC) and biodiversity loss (van Vuuren *et al.*, 2019). To withstand these current and future pressures, there is a need to ensure balanced and integrated people-nature-economy sustainable management of water, food and energy (UN-Water, 2018). The search for integrated resources management led to the polycentric water-energy-food (WEF) nexus approach, which highlights the multifarious interdependence of water, energy and food security and the ecosystem of natural resources that underpin that security – water, soil and land (Hoff, 2011; WEF, 2011). The goal of nexus thinking is maximum synergies and minimum 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.*, 2020a; Carmona-Moreno, 2021). Nexus thinking operates 'out of the water box' at multiple spatial scales to promote co-ownership and engagement across all relevant sectors (Stucki and Smith, 2011; Smith and Clausen, 2015; Grigg, 2019; Sadeghi and Sharifi Moghadam, 2021).

Despite the hype of the WEF nexus approach in different agendas, several authors concur that its translation into practice is lagging due to the unavailability of tools and empirical evidence that can facilitate and support the implementation (Nhamo *et al.*, 2020a; Naidoo *et al.*, 2021; Taguta *et al.*, 2022a). Similarly, (Hoolohan *et al.*, 2018; Hoolohan *et al.*, 2019; Molajou *et al.*, 2021) attribute this lag in implementation to the focus of the majority of previous WEF nexus studies on the history and present, thus leaving the future dynamics and evolution of WEF systems within a changing context unexplored.

The WEF systems and their nexus span multiple sectoral and temporal scales, thus requiring long-sighted approaches that minimize maladaptive pathways (Cremades *et al.*, 2019; Payet-Burin *et al.*, 2019; Nhamo *et al.*, 2020a). Opportunities for robust planning of the uncertain and complex WEF nexus futures lie in scenario planning (Star *et al.*, 2016). Previous applications of scenario planning in studies of global change emphasise its potential applicability as a platform of the interface between decision-makers and uncertain future for an effective gathering of experience across disciplines, sectors, and scales in the WEF nexus to explore how desirable outcomes might be achieved and undesirable outcomes avoided (Borgomeo *et al.*, 2018; O'Neill *et al.*, 2020). However, WEF nexus scenario planning remains vague due to methodological challenges in characterising the future social, technological and environmental conditions in the WEF nexus (Hoolohan *et al.*, 2018). The global aim of this study was to provide a review of the state-of-the-art WEF nexus scenario planning by investigating if and how scenario planning was applied in WEF nexus studies. To fulfil this aim, this study sought to systematically review the available literature and address the following specific objectives:

i. assess if scenario planning was used in the WEF nexus approach,

ii. assess how scenario planning was used in the WEF nexus approach,

iii. propose a generic approach and roadmap for co-developing integrative WEF nexus scenarios.

7.2 Materials and methods

The Preferred Reporting Items guided the review for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page *et al.*, 2021a; Page *et al.*, 2021b), which was also applied by Fernandes Torres *et al.* (2019) in reviewing literature for proposing a systematic procedure to developing nexus thinking management models. The PRISMA steps involved, among others, eligibility criteria, information sources, search strategy, literature screening, selection, data collection, defining data items, and analysis.

7.2.1 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 7.1). The PICOS strategy informed the search strategy and the subsequent inclusion-exclusion criteria.

Table 7.1: The adapted PICOS strategy used for literature searching

PICOS	Description
Population	WEF nexus
Indicator	WEF nexus scenario planning
Comparison	N/A
Outcome	Methods and processes of WEF nexus scenario planning
Study designs	Qualitative, quantitative and mixed

Given the novelty and fast-paced research of 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 and materials from special issue editorial material, and institutional documents, including dissertations, theses, or technical papers, all written and published in English. Similarly, the date of publication, geographic scope, journal disciplines and impact factors were kept open to capture all WEF nexus studies.

7.2.2 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 Web of Science Core Collection (WoS) (Last search on 15 October 2021). These two multidisciplinary databases were selected for their comprehensive coverage and high-quality scientific publications that allow systematic review. Their journal coverage is also remarkably greater than other common databases, even in natural science and engineering disciplines. In addition, citation searches were conducted for publications in databases by international organizations such as Food and Agriculture Organization (FAO), World Bank and International Renewable Energy Agency (IRENA). The search criteria in the two databases (Scopus and WoS) involved searching topics using Boolean expressions. The search topics were formed from the keywords "nexus, scenario*, plan*, forecast*, predict*, future, pathway*, SSP, RCP, RAP", together with iterations of "water, energy, food" and WEF. The details of the search topics used are presented in Table 7.2.

Table 7.2: Terms used in searching literature in Scopus and WoS 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 "representative agricultural pathway" OR RAP)

All records obtained from Scopus, WoS, and other databases were combined to facilitate the removal of duplicates.

7.2.3 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 screened for literature selection. The screening was in favour of publications on (i) the application of scenario development, planning and analysis in the WEF nexus approach in theory and practice, (ii) in a defined geographic scope (location, place, area) and spatial scale, (iii) capturing at least all three components of the WEF nexus: water, energy, and food, with the possibility of additional related dimensions such as climate, environment, and economy, (iv) use of established pathways and protocols such as SSPs, RCPs, RAPs, policies and interventions/response strategies. Sometimes 'land', 'agriculture' ', irrigation' or 'irrigated agriculture' was considered a proxy for food since it is directly linked to food production. Publications missing any of the water, energy and food dimensions and their proxies, as well as books and chapters that replicated some published journal articles, were excluded. Eventually, the eligible papers were retrieved for review. These eligible papers and sources may not include all the WEF nexus literature. However, they best represent the previous work relevant to addressing and fulfilling our research questions and objectives.

7.2.4 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 including publication details (author, year, title), case study (location, country, continent), scale (spatial, temporal), involvement of stakeholders, nexus framework/concept, analytic modelling tool, drivers and pathways (CMIP5 SSPs and RCPs; CMIP6 SSP-RCPs; RAPs, policies/interventions).

7.2.5 Data items, definitions 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 and quantitatively for analysis, visualization, and interpretation. In this study, drivers of change were considered as any driving forces or human-induced factors that directly or indirectly cause a change in the state, behaviour or ecosystem/environment of a WEF system (Carter *et al.*, 2001; MEA, 2005; UNEP, 2012). Such forces or causal factors can be demographic, socioeconomic, sociocultural, political, technological and environmental, and they influence or exert pressure on a system (Postma and Liebl, 2005; Alcamo, 2008; de Loë and Patterson, 2017; Bruaset and Sægrov, 2018). Due to the diversity of regional challenges and priorities of WEF systems, this study analysed the pathways that were considered in different continents. The spatial scales were classified as local (household, field, farm, community, village, town, city, municipality, district), medium (metropolitan, in-country region, provincial, national, state, county, sub-catchment, watershed, in-country river basin/catchment), and large (transboundary river basin and aquifer, economic region, continent, global). The temporal scales or planning horizons were categorised as short-term (1 to 5 years), medium-term (6 to 10 years) and long-term (more than ten years) (Bruaset and Sægrov, 2018). The interventions were referenced to the sector in which their effect is planned to impact resources production, generation, supply, use and consumption.

7.3 Results and discussion

7.3.1 Literature search

The WEF nexus community has attempted to plan scenarios based on the probable evolution of WEF systems subject to drivers and established and unestablished pathways. The search in databases yielded 1997 records (Figure 7.1). Removal of duplicates and screening of the publications by the inclusion-exclusion criteria yielded 187 articles on WEF nexus scenario planning and RAPs development and assessment, respectively that were retrieved and analysed.

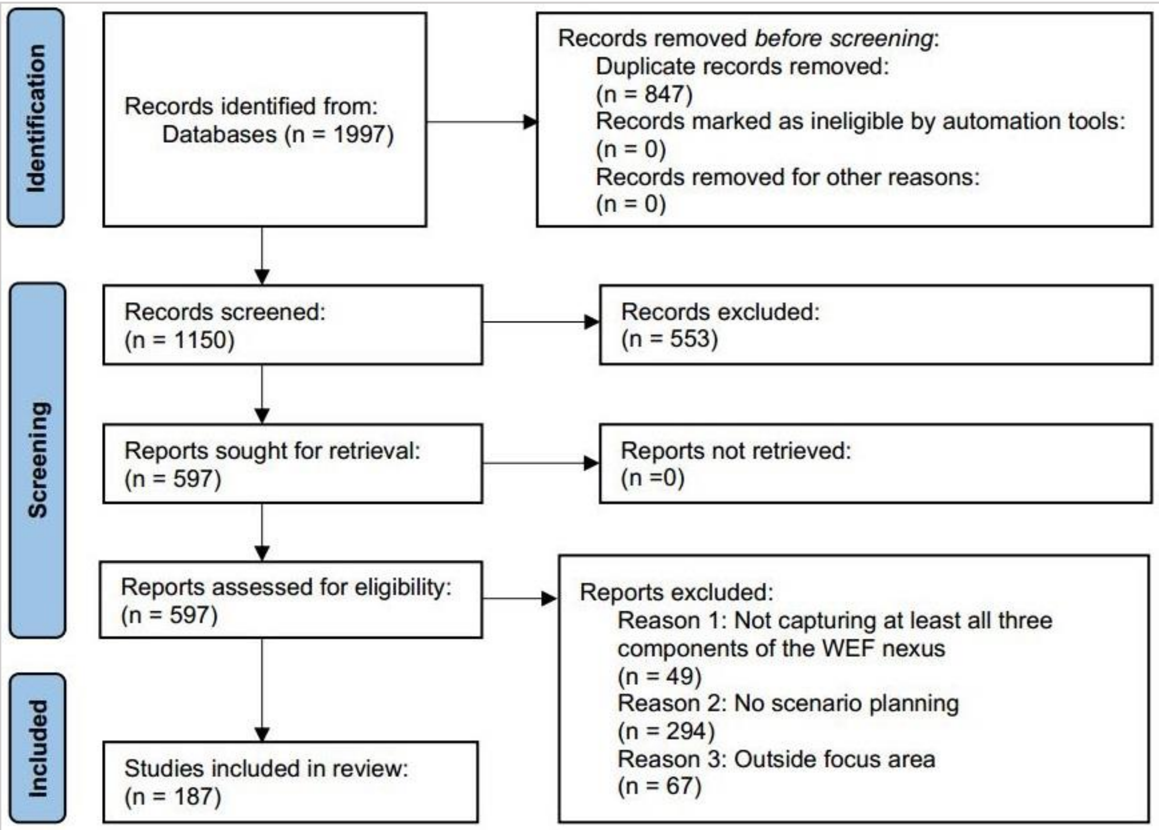


Figure 7.1: PRISMA flow-chart with literature search and screening results for this study

7.3.2 Drivers of change in demand and supply in WEF nexus scenario planning

To explore the future evolution of WEF systems, the drivers of change that were considered to likely change the per-capita resource supply and consumption in published literature are presented in Figure 7.2.

Figure 7.2: Drivers of change considered in WEF nexus scenario planning studies.

The impacts of climate change included dry spells, droughts, and seasonal variability leading to water scarcity and changes in reservoir inflow (Kotir *et al.*, 2016; Jalilov *et al.*, 2018; Uen *et al.*, 2018). Climate change triggers water scarcity, extreme events, and ecological change, which consequently undermines the production and supply of WEF resources (Sivakumar, 2021). According to (FAO, 2022; IPCC, 2022), climate change-induced warmer temperatures and unreliable precipitation amounts and patterns will worsen the pressure on ecosystems and WEF resources. For example, climate change induces extreme events such as floods, droughts and prolonged dry spells, which will affect water availability patterns, with likely knock-on effects on agricultural productivity and hydropower generation (Caretta *et al.*, 2022; FAO, 2022; IPCC, 2022; Kerr *et al.*, 2022). Relatedly, environmental issues that were factored into

WEF nexus scenario planning include greenhouse gas (GHG) emissions, soil degradation and downstream flow obligations (da Silva and de Moraes, 2018; Uden *et al.*, 2018; van Vuuren *et al.*, 2019). For economic factors, considerations were taken for economic and industrial growth (e.g. International Monetary Fund (IMF)'s gross domestic product (GDP) trends) (Sušnik *et al.*, 2018; Khan *et al.*, 2021; Wang *et al.*, 2021b), social impact cost, discount rates and capital costs on WEF investments and natural capital (Intralawan *et al.*, 2018; Almulla *et al.*, 2020; Koundouri and Papadaki, 2020), as well as economic benefits such as system profit (Li *et al.*, 2019; Ji *et al.*, 2020; Li *et al.*, 2021). The continued development and growth of economies in an urbanizing world increase resource demand (UN-DESA, 2019; FAO, 2022).

The socioeconomic drivers included demographics such as population growth in the form of increases (Bazzana *et al.*, 2020; Bao *et al.*, 2021; El-Gafy and Apul, 2021), decreases (Naderi *et al.*, 2021), birth rate (low, median, high) (Jin *et al.*, 2019), and family size (Hussien *et al.*, 2017). Future trends in migration and urbanization were also considered (Gallagher *et al.*, 2020; Niva *et al.*, 2020; Terrapon-Pfaff *et al.*, 2021), as well as changes in lifestyle and intake of protein, fat and calorie intake (van Vuuren *et al.*, 2015; Ringler *et al.*, 2016). The global population has more than tripled since the middle of the 20th century to reach about 8 billion, with expectations to hit the 9.7 billion mark by the year 2050 (Smith and Clausen, 2015; UN-DESA, 2021; UN-DESA, 2022). Population growth and demographic shifts will influence WEF governance and increase demands on available WEF resources (FAO, 2014). The same effect is likely due to urbanization, rising income levels, increasing standards of living, and shifts in dietary patterns on demand, quality and quantity of WEF resources (Sivakumar, 2021). Changes in the amount and types of food consumed towards more resource-intensive meat and dairy foods exacerbate the burden of population growth on increasing demand for food (UN-Water, 2018; UN-DESA, 2021). This situation will also require expanding electricity generation infrastructure and biofuel production, which alters natural hydrology and demand more land and water resources (Basson, 2005; Schmutz and Moog, 2018; SDSN/FEEM, 2021). Increased electricity production will require more water for cooling thermal plants and turning turbines in hydropower plants (de Loë and Patterson, 2017). Land use drivers delved into proportions and expansion of agricultural land (El Gafy *et al.*, 2017; Bijl *et al.*, 2018; de Vos *et al.*, 2021) and urbanization (Bremer *et al.*, 2018; Niva *et al.*, 2020; Naderi *et al.*, 2021). Such changes in land use for agricultural production and urbanization will affect water supply, demand and quality due to alterations in hydrology (and hence quantity), consumption and use (de Loë and Patterson, 2017).

WEF nexus scenarios by (Bazzana *et al.*, 2021) were partly driven by the perception of ecological risk between traditionalists and innovators, while (Ramirez *et al.*, 2021) factored in water-consumption behaviour of farmers towards changes in irrigation water pricing and their willingness to pay. (Chen and Xu, 2021) considered growth of the social economy, science and technology with levels such as slow, improved and significant; while (Hussien *et al.*, 2017; Fan *et al.*, 2019) took into account farmers' income such as salary. Consideration for science and technology looked at development and advances in innovation, which may alter the production and supply of WEF resources (Hejazi *et al.*, 2014a; Hejazi *et al.*, 2014b; van Vuuren *et al.*, 2015).

7.3.3 Scales (spatial, temporal) and analytic tools in WEF nexus scenario planning

The spatial scales were classified as local (household, field, farm, community, village, town, city, municipality, district), medium (metropolitan, in-country region, provincial, national, state, county, sub-catchment, watershed, in-country river basin/catchment), and large (transboundary river basin and aquifer, economic region, continent, global). The planning of WEF nexus scenarios at medium spatial scales dominates at about 52% of the reviewed studies, with large (31%) and local scale studies (17%) sharing the other half (Figure 7.3a). This shows a critical gap in WEF nexus scenario planning at local scales where challenges are felt and interventions are actionable.

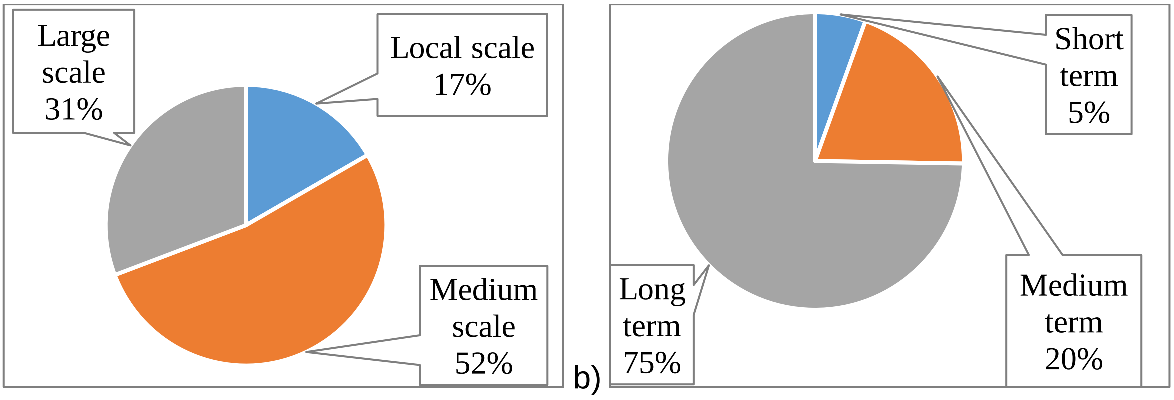
a) 

Figure 7.3: (a) Spatial and (b) temporal scales in WEF nexus scenario planning

The temporal scales or planning horizons were categorised as short-term (1 to 5 years), medium-term (6 to 10 years) and long-term (more than ten years). Concerning the temporal scale, long-term planning horizons dominate (75%), followed by medium-term horizons (20%) and short-term horizons (5%) (Figure 7.3b). The consideration and dominance of long-term planning horizons in WEF nexus scenario planning are 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 (Adom *et al.*, 2022; Salem *et al.*, 2022) (Naidoo *et al.*, 2021). Even short- and medium-term interventions have long-term consequences which need to be accounted for (Cremades *et al.*, 2019).

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

Several analytic tools have been used to analyse WEF nexus scenarios across different spatial scales, from small or local, through medium to large scales. At the local spatial scales, the most used modelling tools include agent-based modelling (ABM) (Ding *et al.*, 2019; Ding *et al.*, 2021), system dynamics modelling (SDM) (Casazza *et al.*, 2021; Valencia *et al.*, 2022; Wen *et al.*, 2022), life cycle assessment (LCA) (Toboso-Chavero *et al.*, 2021; Valencia *et al.*, 2022), hydrologic models, and crop simulation models. ABM modelling is usually coupled to the Monte Carlo simulation technique for randomly generating and running long-term simulations and analysing probable WEF scenarios (Bazzana *et al.*, 2020; Bazzana *et al.*, 2021). SDM and LCA were applied at household, building, housing estate, and city scales. Hydrologic models that were used to simulate water resource dynamics in the WEF nexus at local scales include SWAT, the Lund-Potsdam-Jena model (LPJmL), a regional hydrologic model and a classical node-link river basin simulator (Ding *et al.*, 2019; Geressu *et al.*, 2020; Ding *et al.*, 2021; Zhang and Ren, 2021). Crop simulation models were also applied at these small scales (county, plantation, farm, village), and they include DSSAT (Phetheet *et al.*, 2021), AquaCrop and Global Agro-Ecological Zones (GAEZ) (Bao *et al.*, 2021). Other WEF nexus models that were applied at local scales include the WEF (water-energy-food) model (Hussien *et al.*, 2017; Hussien *et al.*, 2018), Food-Energy-Water Calculator (FEWCalc) (Phetheet *et al.*, 2021), City Geography Markup Language (CityGML) and MuSIASEM (Toboso-Chavero *et al.*, 2021). The reader is referred to their founding publications for detailed information about these models.

At medium spatial scales, the analytic tools that were applied in planning WEF nexus scenarios include ABM (Bieber *et al.*, 2018; Abdel-Aal *et al.*, 2020), SDM (Laspidou *et al.*, 2020; Ravar *et al.*, 2020; Purwanto *et al.*, 2021), optimization models (Tian *et al.*, 2018; Allam and Eltahir, 2019; Saif *et al.*, 2020), hydro-economic models (Yang *et al.*, 2016; Jalilov *et al.*, 2018), hydrological models, LCA (Yuan *et al.*, 2018; Chen *et al.*, 2020; Xu *et al.*, 2020), cost-minimizing models (Gao *et al.*, 2018; Ramirez *et al.*, 2021), crop simulation models, cost-benefit analysis (Sishodia *et al.*, 2017) and fuzzy cognitive mapping (FCM) (Martinez *et al.*, 2018; Ziv *et al.*, 2018). The hydrological models included Soil and Water Integrated Model (SWIM) (da Silva and de Moraes, 2018), Vmod (Keskinen *et al.*, 2015; Laspidou *et al.*, 2020), MIKE SHE/MIKE 11 (Sishodia *et al.*, 2017; Sishodia *et al.*, 2018), SWAT (Schull *et al.*, 2020), and HYMOD_DS (Yang *et al.*, 2016). The crop simulation and related models used for simulating food and fibre production in WEF nexus scenario planning include CROPWAT, CLIMWAT, AquaCrop, and DSSAT (Lee *et al.*, 2018; Lee *et al.*, 2020a; Lee *et al.*, 2020b). Some models dedicated to the WEF nexus were also applied in WEF nexus scenario planning, and they include WEAP-LEAP (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017; Nasrollahi *et al.*, 2021), WEF Nexus Tool 2.0 (Daher and Mohtar, 2015; Degirmencioglu *et al.*, 2019; Karim and Daher, 2021), Common Agricultural Policy Regionalised Impact (CAPRI) (González-Rosell *et al.*, 2020; Sušnik *et al.*, 2021), Global Change Assessment Model (GCAM) (Khan *et al.*, 2020; Khan *et al.*, 2021; Wild *et al.*, 2021), Q-Nexus (Karnib, 2018), OSeMOSYS (Laspidou *et al.*, 2020), GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus (GREAT for FEW) (Lin *et al.*, 2019), WEFSiM (Wicaksono *et al.*, 2017; Wicaksono and Kang, 2019; Wicaksono *et al.*, 2020), Urban Circular Economy Calculator (UCEC) (Xue *et al.*, 2018), Agricultural Water-Energy-Food Sustainable Management (AWEFSM) model (Li *et al.*, 2019), and Energy Portfolio Assessment Tool (EPAT) (Mroue *et al.*, 2019). The reader is referred to their founding publications for detailed information about these models.

At large scales, WEF nexus scenarios were planned with the use of analytic tools, including the Integrated Model to Assess the Global Environment (IMAGE) (van Vuuren *et al.*, 2015; Bijl *et al.*, 2018; van Vuuren *et al.*, 2019), GCAM (Hejazi *et al.*, 2014a; Hejazi *et al.*, 2014b; Borgomeo *et al.*, 2018; Miralles-Wilhelm *et al.*, 2018), hydrologic models, crop simulation models, hydro-economic model (Jalilov *et al.*, 2016; Yang *et al.*, 2016; Do *et al.*, 2020), WEAP (Amjath-Babu *et al.*, 2019; Kolusu *et al.*, 2021; Siderius *et al.*, 2021), optimization models (Damerau *et al.*, 2016; Dhaubanjar *et al.*, 2017; Cansino-Loeza and Ponce-Ortega, 2021; Radmehr *et al.*, 2021), and system dynamics modelling (SDM) (Elsayed *et al.*, 2020; Gallagher *et al.*, 2020; Naderi *et al.*, 2021). The hydrologic models included LPJmL (Bijl *et al.*, 2018; van Vuuren *et al.*, 2019; de Vos *et al.*, 2021; Kolusu *et al.*, 2021; Siderius *et al.*, 2021), SWAT (Yang *et al.*, 2018), Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) and RiverWare (Basheer *et al.*, 2018), Spatial Processes In Hydrology (SPHY) (Dhaubanjar *et al.*, 2021), Vmod (Hoang *et al.*, 2019), and Integrated Catchment Model (INCA) (Jin *et al.*, 2018). The crop simulation models included CROPWAT (Basheer *et al.*, 2018), DSSAT (Amjath-Babu *et al.*, 2019), GAEZ (Zhong etal2021), Global Crop Water Model (GCWM) (Qin, 2021) and a crop simulation module (Hoang *et al.*, 2019). Other WEF nexus tools that were applied in planning scenarios at large scales include Nexus Webs (Colloff *et al.*, 2019), Nexus Solutions Tool (NEST) (Wada *et al.*, 2019; Vinca *et al.*, 2020; Vinca *et al.*, 2021), Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF) (Payet-Burin *et al.*, 2019; Payet-Burin *et al.*, 2021), and Decision-Analytic Framework to explore the water-energy-food NExus (DAFNE) (Koundouri and Papadaki, 2020). The reader is referred to their founding publications for detailed information about these models.

7.3.4 Pathways in long-term WEF nexus scenario planning case studies

7.3.4.1 Use of socioeconomic and climate change pathways in WEF nexus scenario planning

Several pathways were integrated in WEF nexus scenario planning studies based on the drivers of change (Section 7.3.2). 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). Societal and climatic futures are explored with socioeconomic pathways (SSPs), climate (RCPs), and integrated pathways (SSP-RCPs). These pathways have been developed and continuously improved in progressive phases of the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP). The outcomes of the Coupled Model Intercomparison Project fifth phase (CMIP5) included five SSPs and four RCPs. SSPs are five basic reference pathways describing probable global socioeconomic developments that would point in the future to different challenges for mitigation and adaptation to climate change in the absence of climate change, climate impacts or climate policies and responses. On the other hand, the four RCPs are a scenario set defining specific multi-gas emission, concentration and land-use trajectories and subsequent radiative forcing, from 2.6 to 8.5 W/m^2. For detailed information on the SSPs, RCPs and their attributes, the reader is referred to their founding publications (Moss *et al.*, 2010; van Vuuren *et al.*, 2011; O'Neill *et al.*, 2014; Riahi *et al.*, 2017).

In the Scenario Model Intercomparison Project (ScenarioMIP), the SSPs and RCPs from CMIP5 were coupled into integrated SSP-RCP pathways in CMIP6 to better assess and address the impact of climate mitigation and adaptation policy through enhanced integrative socioeconomic coupling, in different future scenarios (O'Neill *et al.*, 2016; Simpkins, 2017; Siqueira *et al.*, 2021). The recently published CMIP6 integrated CMIP6 SSP-RCP pathways span the same range as their CMIP5 counterparts but fill critical gaps, including RCP 1.9, RCP 3.4, and RCP 7.0 to address intermediate forcing levels and questions (Eyring *et al.*, 2016). These recently published pathways attempt to encompass a range of potential futures characterized by the evolution of challenges to the mitigation of and mitigation to climate change (Liddicoat *et al.*, 2021). The reader is referred to the founding publications for detailed information about the CMIP6 SSP-RCP pathways (Eyring *et al.*, 2016; Rogelj *et al.*, 2018; Gidden *et al.*, 2019; Hausfather, 2019; O'Neill *et al.*, 2020).

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

A minority (about 11%) of the reviewed studies utilized SSPs in representing the dynamics of socio-economic change in WEF nexus scenario planning. Across all world regions, the dominant SSP in WEF nexus scenario planning is the 'middle of the road' pathway SSP2 which is usually used as the baseline or business-as-usual (BAU) pathway representing a future with intermediate challenges to mitigation and adaptation (Figure 7.4).

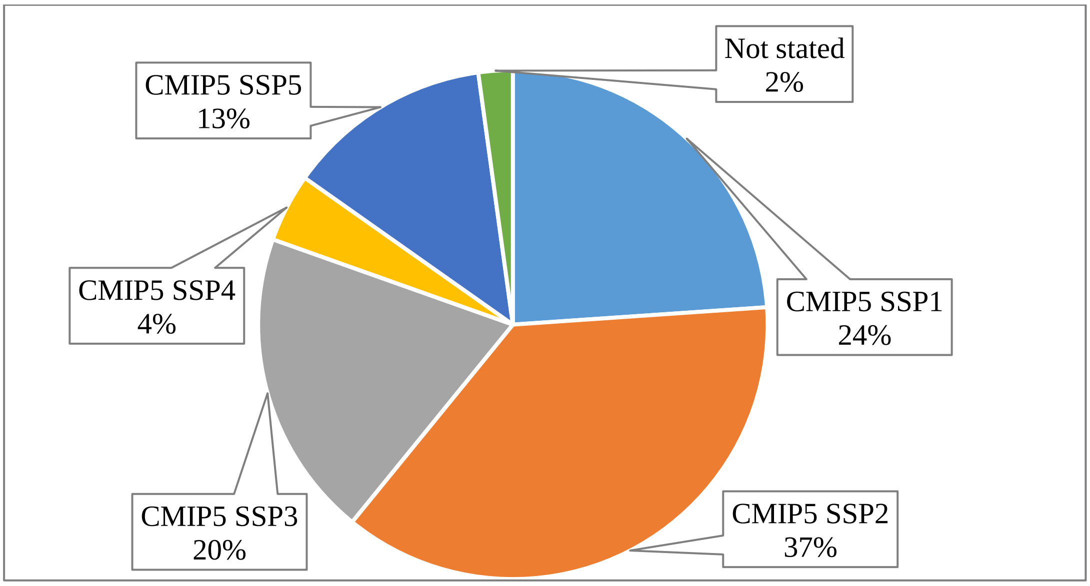


Figure 7.4: Application of pre-CMIP5 and CMIP5 socioeconomic pathways in WEF nexus scenario planning

This is followed by SSPs 1 and 2. SSP2 is the pathway for 'taking the green road of sustainability', representing a future of low challenges to mitigation and adaptation. SSP3 of 'regional rivalry' portrays high challenges to mitigation and adaptation. The third frequent pathway is SSP5 or 'conventional fossil-fuelled development', representing a future of high and low challenges to mitigation and adaptation, respectively. The least frequent is SSP4 or 'a road divided by inequality', representing future low and high challenges to mitigation and adaptation, respectively (O'Neill *et al.*, 2014; O'Neill *et al.*, 2017).

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

About 30% of reviewed literature applied established climate change pathways (RCPs and SRES) in their studies. Across all regions, the descending order of frequency in applying climate change pathways is RCP4.5 and RCP8.5 with almost similar frequency, followed by RCP2.6 and RCP6.0 with almost similar frequency, others, with RCP7.5 and RCP3.4 coming last with almost similar frequency (Figure 7.5).

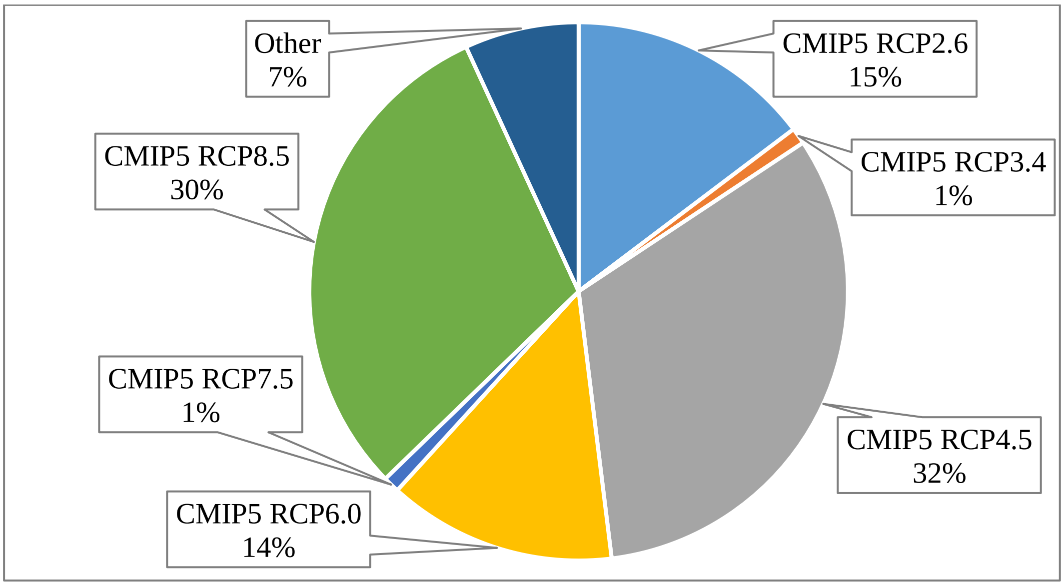


Figure 7.5: Application of pre-CMIP5 and CMIP5 climate change pathways in WEF nexus scenario planning

The SRES family of pathways were applied in WEF nexus scenario studies by Khan *et al.* (2017) (A2 and B2), da Silva and de Moraes (2018) (A2) and (Keskinen *et al.*, 2015) (B1 and A1b). The SRES A1 pathway represented a future world of rapid economic growth, a global population that peaks mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. This pathway focuses on economic and cultural convergence and capacity building, substantially reducing regional differences in per capita income. The A1b scenario was part of the A1 scenario family. It was characterized by a balanced technological change in the energy system across all sources, such as fossil-intensive and non-fossil energy sources (Carter *et al.*, 2001). The SRES A2 pathway represented a future differentiated and heterogeneous world focused on self-reliance and preserving local identities. In this pathway, fertility patterns across regions converge very slowly, increasing population continuously. Economic development is primarily regionally orientated, and per capita, economic growth and technological change are more fragmented and slower than other storylines (IPCC, 2000). The SRES B1 represented a future convergent world with global population growth similar to A1 but with rapid changes in economic structures toward a service and information economy, reductions in material intensity, and the introduction of clean and resource-efficient technologies. This pathway emphasises global economic, social, and environmental sustainability solutions, including improved equity, but without additional climate change policies and initiatives (Nakicenovic *et al.*, 2000). The SRES B2 represented a future world emphasising local solutions to economic, social, and environmental sustainability. This pathway is consistent with a world of continuously increasing global population at a lower rate than in scenario A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. Although this scenario also is orientated toward environmental protection and social equity, it focuses on the local and regional levels (Abram *et al.*, 2019).

Other studies incorporated climate change by climate stress tests involving levels of temperature and precipitation changes (Yang *et al.*, 2016) such as dry, semi-dry, intermediate semi-wet, and wet future climate (Karlberg *et al.*, 2015; Payet-Burin *et al.*, 2021; Phetheet *et al.*, 2021; Wang *et al.*, 2021a), as well as warmer or cooler temperatures than normal (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017;

Degirmencioglu *et al.*, 2019), and warming scenarios above pre-industrial global mean temperature such as 1.5°C (least severe), 2.0°C, 2.5°C, and 3.0-4.0°C (most severe) (Ding *et al.*, 2019; Ding *et al.*, 2021; Qin, 2021). Karan *et al.* (2018) classified climate pathways as cloudy, humid, sunny and arid in developing their WEF nexus scenarios.

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

Only one study by Wang *et al.* (2021a) used the recently published CMIP6 SSP-RCP pathways in a WEF nexus scenario planning study in the Mekong river delta. Accordingly, only five SSP-RCPs were applied equally in the case study, including SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5. In their study, Wang *et al.* (2021a) used five CMIP6 pathways in the impact assessment of climate and socioeconomic changes on rice yield, power generation and water withdrawal in Vietnam. Attributes such as emissions trajectories for some CMIP6 SSP-RCP pathways are illustrated in Figure 7.6.

(a) Scenario Name	SSP	Target 2100 Forcing Level (W m^{-2})	Scenario Type	Forcing Category
SSP1-1.9	1	1.9	Mitigation	Low
SSP1-2.6	1	2.6	Mitigation	Low
SSP2-4.5	2	4.5	Mitigation	Medium
SSP3-7.0	3	7	Baseline	High
SSP3-LowNTCF	3	6.3	Mitigation	Medium
SSP4-3.4	4	3.4	Mitigation	Low
SSP4-6.0	4	6	Mitigation	Medium
SSP5-3.4-OS	5	3.4	Mitigation	Overshoot
SSP5-8.5	5	8.5	Baseline	High

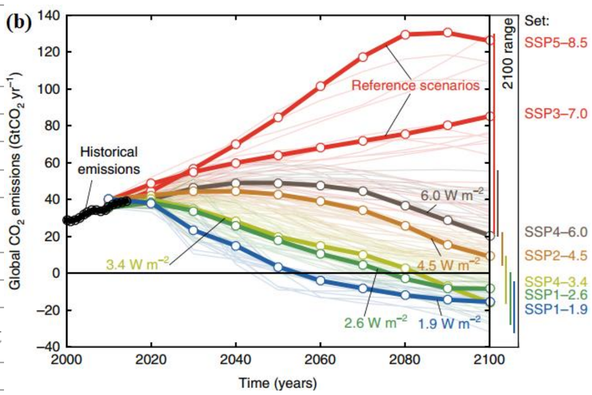


Figure 7.6: (a) Attributes of all CMIP6 scenarios after (O'Neill et al., 2016; Gidden et al., 2019), (b) future global CO_2 emissions of SSP-RCP scenarios in CMIP6 with historical emissions in black (O'Neill *et al.*, 2016; Rogelj *et al.*, 2018; Abram *et al.*, 2019; Gidden *et al.*, 2019; Hausfather, 2019; O'Neill *et al.*, 2020; IPCC, 2021)

According to Wang *et al.* (2021a), SSP1-2.6 is the pathway with low societal vulnerability and forcing level, while SSP2-4.5 is the middle-of-the-road pathway that combines intermediate challenges for mitigation and forcing signal. On the hand, SSP3-7.0 represents medium-high future mitigation and forcing pathways, while SSP4-6.0 is in the range of medium-forcing pathways with a high challenge to adaptation. SSP5-8.5 is the pathway that represents a future with high emissions of greenhouse gas and a high challenge to mitigation and adaptation (Wang *et al.*, 2021a).

7.3.4.2 Pathways from interventions to manage supply and demand of WEF resources for WEF nexus scenario planning

Societies may be provoked by changes in WEF drivers to implement mitigation and adaptive actions. Other WEF nexus studies planned their scenarios without explicit specification of RCPs, SSPs and RAPs in pursuit of understanding and highlighting the impacts of certain interventions on linkages between nexus components in alternative futures. They used unestablished pathways for the evolution of WEF systems. Here we categorised and analysed such interventions as either cross-cutting or by the specific sectors in which they planned to affect resources production, generation, supply, use and consumption.

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 7.3).

Table 7.3: 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

The policy and governance frameworks were considered at national, regional and international levels. Examples at the national level included national 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 (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 intervention that was considered is 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.*, 2021), 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; Allam and Eltahir, 2019; Wada *et al.*, 2019; Verhagen *et al.*, 2021; 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 innovation 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.*, 2021; Sušnik *et al.*, 2021). Information campaigns were considered for 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.*, 2021a). Examples of media channels for these measures include newspapers, television (TV) advertisements, and posters (Casazza *et al.*, 2021).

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 7.4).

Table 7.4: 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

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). At the watershed scale, the 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.*, 2019a; Ramirez *et al.*, 2021).

For increasing water-use efficiency, specific measures included reducing non-revenue water and use of irrigation systems that have high efficiency in pumping, conveyance and application, for example, drip, bubbler and sprinkler irrigation systems (da Silva and de Moraes, 2018; 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). Monitoring agricultural water use and productivity techniques 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; Gao *et al.*, 2021; Terrapon-Pfaff *et al.*, 2021). Similar interventions included reducing cleaning water consumption in power generation plants using waterless cleaning technologies, which is 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 use of 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 with a component of 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, for example, irrigation (Bieber *et al.*, 2018; Ramirez *et al.*, 2021). Measures for water resources protection to enhance water quantity and quality included controlling wastewater return flow recharge and improving water infrastructure and management (Martinez *et al.*, 2018; Fan *et al.*, 2019; 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.

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 augment 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 7.5).

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 (Bieber *et al.*, 2018; Yang *et al.*, 2018; Amjath-Babu *et al.*, 2019; Dhaubanjar *et al.*, 2021; Siderius *et al.*, 2021). For power cogeneration units, pathways are considered 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 LPG, biogas, and biomass pellets (Karlberg *et al.*, 2015; van Vuuren *et al.*, 2015; Kaddoura and El Khatib, 2017; Sušnik *et al.*, 2021). The technology for bioenergy production included anaerobic biogas digesters (Xue *et al.*, 2018; Hoolohan *et al.*, 2019; Abdel-Aal *et al.*, 2020; Larkin *et al.*, 2020), while the sources of bioenergy included biomass (miscanthus, algae), crops (sugarcane, corn, sewerage, rape, canola, wheat), and waste (Walsh *et al.*, 2016; Schwanitz *et al.*, 2017; Xue *et al.*, 2018). Regulatory interventions included restriction of biomass use for fodder and fuel (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017).

Table 7.5: 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

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 agricultural yields and productivity, (ii) good agricultural practices, (iii) agricultural land expansion, (iv) policy and regulation, (v) irrigation, (vi) improve efficiency, (vii) change diet, lifestyle, and consumption patterns, and (viii) alternative foods (Table 7.6).

Table 7.6: 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

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; Shi *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, a 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 of food crops (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).

7.3.5 Pathways for agricultural development in scenario planning

Agriculture is historically central to the link between people and natural systems by providing food, fibre and energy while relying strongly on land, water and energy resources (Ruane *et al.*, 2017). The sector's multiple global challenges include producing adequate food and nutrition for the growing population, providing sustainable livelihoods for farmers, and reducing detrimental environmental effects while addressing climate vulnerability and change (Rosenzweig *et al.*, 2021). The evolution of agricultural (crop and livestock production) systems was included in WEF nexus scenario planning as interventions (Section "Food sector interventions used in WEF nexus scenario planning studies") without explicit use of established pathways such as RAPs.

RAPs project plausible future biophysical and socioeconomic conditions used for agricultural model inter-comparison, improvement, and integrated impact assessment for a particular location, in a manner consistent with the new global pathways and scenarios (Valdivia *et al.*, 2015; Antle and Valdivia, 2016). They are combinations of economic, technology and policy or institutional drivers, qualitatively and quantitatively, applicable with the crop, livestock and economic models to represent future management (e.g. use of improved crop varieties), future prices and socioeconomic conditions (e.g. changes in policies, changes in farm size and household size) (Valdivia *et al.*, 2015; Tumbo *et al.*, 2020; Antle and Valdivia, 2021). For detailed information on RAPs, including their pathway descriptions, and matrices of synergies and trade-offs, the reader is referred to the founding publications (Valdivia *et al.*, 2015; Antle and Valdivia, 2016; Rosenzweig *et al.*, 2016).

Studies on RAPs were conducted in approximately 32 non-WEF nexus studies across all regions. RAPs were developed and applied to include optimistic, business-as-usual (BAU) and pessimistic pathways and were used to drive crop simulation models in impact assessments. The BAU considered continuing historical trends through the present into the future. At the same time, the optimistic and pessimistic RAPs characterized sustainable development and a dysfunctional world with unsustainable development (e.g. a rapid economic, top range of greenhouse gas (GHG) concentration, and high challenges to mitigation and adaptation), respectively (Antle *et al.*, 2015c; Mu *et al.*, 2019; Homann-Kee Tui *et al.*, 2021b). For example, the optimistic, BAU and pessimistic RAPs by Valdivia *et al.* (2017), in line with Kenya Vision 2030, were fast implementation, a continuation of current growth trends, and slow implementation, respectively. On the other hand, (Claessens *et al.*, 2012; Ahmad *et al.*, 2015; Descheemaeker *et al.*, 2018) hinged their RAPs on stagnation, change and advances in climate, technology and adaptation efforts. However, other variants of these major RAPs were also considered hinged on costs of production and prices of commodities (Antle *et al.*, 2015b; Antle *et al.*, 2015a; Antle *et al.*, 2015c), prices of inputs (Mu *et al.*, 2019), and climate change adaption strategies including levels of nitrogenous fertilizer application, adjusting sowing dates, changing plant population and development of heat-tolerant cultivars (Ahmad *et al.*, 2020); microdosing and cereal-legume crop rotation (Antle *et al.*, 2018a); as well as improved maize varieties and dual purpose crops (Claessens *et al.*, 2012).

In some cases, the RAPs were developed and assessed based on CMIP5 SSPs and RCPs for capturing temporal evolution in socioeconomic conditions and climate change, respectively. For example, consistent with the established CMIP5's five SSPs, (Mitter *et al.*, 2019; Mitter *et al.*, 2020) developed five RAPs for Europe, and they specifically called them Shared Socio-economic Pathways for European agriculture and food systems (Eur-Agri-SSPs). Eur-Agri-SSP1, Eur-Agri-SSP2, Eur-Agri-SSP3, Eur-Agri-SSP4, and Eur-Agri-SSP5 are characterized by agriculture on (i) sustainable paths, (ii) established paths, (iii) separated paths, (iv) unequal paths, and (v) high-tech paths, respectively (Mitter *et al.*, 2020). Similarly, Biewald *et al.* (2017) extended the established CMIP5's five SSPs to propose RAPs for European Union (EU) agriculture (EU-RAPs). These include EU-RAP1 (sustainable Europe) with a strong Common Agricultural Policy (CAP), a strong focus on environmental regulation (e.g. greening, mitigation), and no producer support (direct payments) (Biewald *et al.*, 2017). EU-RAP2 (middle of the road) represents the BAU with historical and current trends continuing. At the same time, EU-RAP3 (fragmented Europe) expects an EU break up, no CAP, and rich countries to support farmers with national subsidies, while developing countries do not (Biewald *et al.*, 2017). EU-RAP4 (two Europes) divides Europe into poor and rich parts, with a strong green and environmentally friendly CAP in the remaining small and rich EU countries. In contrast, the singled-out developing countries will lack CAP and domestic subsidies (Biewald *et al.*, 2017). EU-RAP5 (fossil-fuelled Europe) consists of a free market world, strong institutions, a strong EU, and weak environmental regulations, with a lack of domestic policies, CAP and mitigation (Biewald *et al.*, 2017).

The studies considered both baseline and long-term future horizons in their RAPs assessments. The common baseline horizons included historical periods such as 1950-2005 (Antle *et al.*, 2018a; Antle *et al.*, 2018b), 1976-2005 (Mu *et al.*, 2019), and 1980-2010 (Homann-Kee Tui *et al.*, 2015; Masikati *et al.*, 2017; Naqvi *et al.*, 2019). Future horizons for modelling and simulations included (i) the near future, such as the 2030s (2010 to 2039) (Mu *et al.*, 2019; Cammarano *et al.*, 2020), (ii) mid-20th century (or 2050s), such as 2040-2070 (Ahmad *et al.*, 2015; Zubair *et al.*, 2015; Anser *et al.*, 2020), and (iii) far future such as 2070s (2070 to 2099) (Antle *et al.*, 2018b; Mu *et al.*, 2019; Cammarano *et al.*, 2020).

7.3.5.1 The use of modelling tools in planning RAPs across scales

RAPs are used to drive models such as crop simulation models (CSMs) or crop models, which represent the growth, development, and yield of plants in impact, climate change and variability assessment studies, for informing long-term planning in food security, developing strategies for adapting to and mitigating climate change and climate variability (Hoogenboom *et al.*, 2004; Chisanga *et al.*, 2017).

Different agricultural economic, crop, livestock, and land-use modelling tools were used in RAPs studies. The agricultural economic models include the Trade-off Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) (Adiku *et al.*, 2015; Ahmad *et al.*, 2015; Homann-Kee Tui *et al.*, 2021b) and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Adiku *et al.*, 2015; Ahmad *et al.*, 2015). The crop simulation models include CropSyst (Antle *et al.*, 2015a; Antle *et al.*, 2015c; Antle *et al.*, 2017b), DSSAT (Zubair *et al.*, 2015; Zamudio, 2016; Tumbo *et al.*, 2020), APSIM (Descheemaeker *et al.*, 2018; Naqvi *et al.*, 2019; Cammarano *et al.*, 2020), and Environmental Policy Integrated Climate Model (EPIC) (Palazzo *et al.*, 2014; Palazzo *et al.*, 2016a; Palazzo *et al.*, 2016b; Palazzo *et al.*, 2017). The livestock/pastures simulation models include GRASP and LIVestock SIMulator (LIVSIM) (Homann-Kee Tui *et al.*, 2020; Homann-Kee Tui *et al.*, 2021a; Homann-Kee Tui *et al.*, 2021b), while the land-use change models include Global Biosphere Management Model (GLOBIOM) and LandShift (Palazzo *et al.*, 2014; Palazzo *et al.*, 2016a; Palazzo *et al.*, 2016b; Palazzo *et al.*, 2017). Some studies applied multiple modelling tools whose ensembles ensure characterization and reduction of uncertainty (Rosenzweig *et al.*, 2021).

7.3.6 Previous attempts to integrate pre-CMIP5 and CMIP5 socioeconomic and climate pathways in WEF nexus scenario planning and RAPs studies

WEF nexus scenario planning and RAPs studies have attempted to integrate CMIP5 SSPs and RCPs in assessing the impacts of changes in socioeconomic and climate conditions (Figure 7.7).

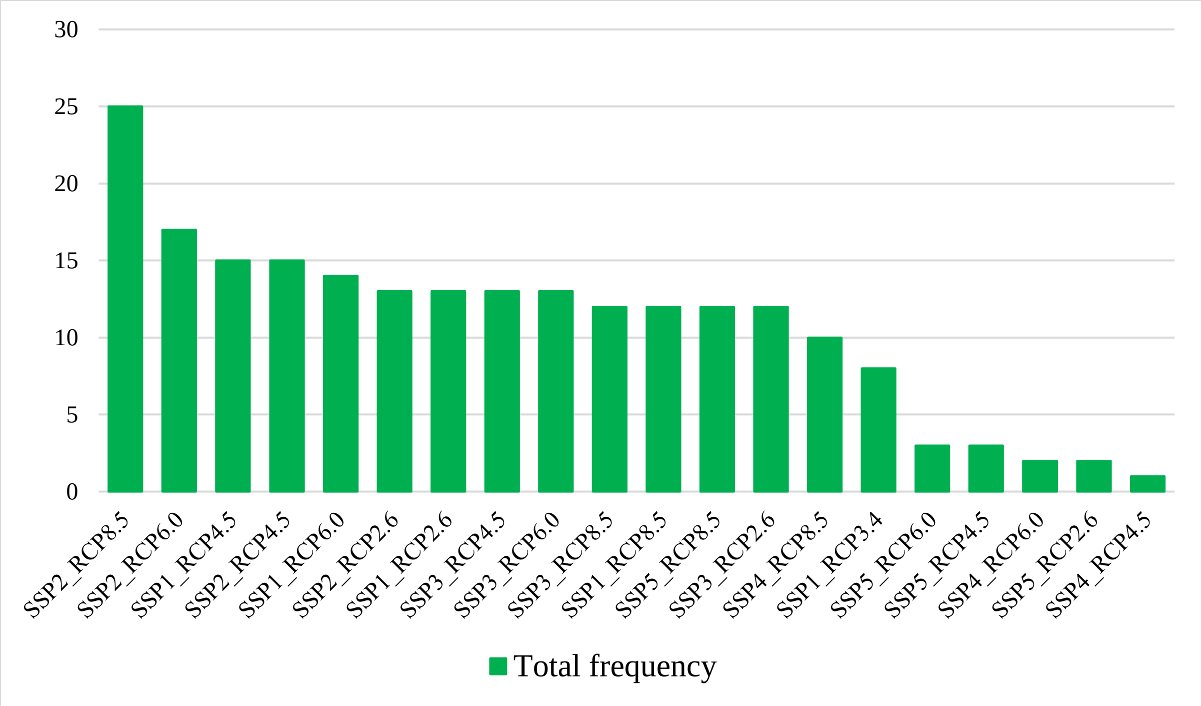


Figure 7.7: Frequency of integrated pre-CMIP5 and CMIP5 socio-economic and climate pathways in WEF nexus scenario planning and RAPs studies

The attributes of this integrative pre-CMIP5 and CMIP5 socio-economic and climate pathways can be inferred from Table 7.7.

Table 7.7: Attributes of the commonly integrated pre-CMIP5 and CMIP5 socio-economic and climate pathways in WEF nexus scenario planning and RAPs studies, in descending order of frequency.

Pathway	**Attributes**	
SSP	**Socioeconomic challenges to mitigation**	**Socioeconomic challenges to adaptation**
2	Intermediate	Intermediate
1	Low	Low
3	High	High
5	High	Low
4	Low	High
RCP	**Emission trajectory**	
8.5	Radiative forcing of greater than 8.5 W/m^2 in 2100	
6.0	A radiative forcing of ~6.0 W/m^2 at stabilization after 2100	
4.5	A radiative forcing of ~4.5 W/m^2 at stabilization after 2100	
2.6	Peak at ~3 W/m^2 before 2100 and then declines. Stays below 2.0°C warming relative to 1850-1900 (median) with implied net zero emissions in the second half of the century	
3.4	Intermediate radiative forcing that reaches a level of 3.4 W/m^2 in 2100. Radiative forcing in the early decades of the 21^{st} century is close to SSP4-6.0, with end-of-century radiative forcing between SSP1-2.6 and SSP2-4.5. It explores the space between scenarios that generally limit warming to below 2°C and around 3°C by 2100.	

Sources: (Moss *et al.*, 2010; van Vuuren *et al.*, 2011; O'Neill *et al.*, 2014; O'Neill *et al.*, 2016; Riahi *et al.*, 2017; Abram *et al.*, 2019; Gidden *et al.*, 2019; Meinshausen *et al.*, 2020; IPCC, 2021; Liddicoat *et al.*, 2021)

These climate, societal and agricultural futures should be integrated with caution on the plausibility and feasibility of particular combinations of SSPs and RCPs. For example, the literature review by O'Neill *et al.* (2020) emphasizes that SSPs 1 to 4 are unlikely with RCP8.5, which can be achieved only by SSP5, while RCP1.9 and RCP2.6 are not achievable under SSP3. O'Neill *et al.* (2020) recommend a typical approach to model-based scenario analysis to investigate the effects of introducing a feature of interest by comparing a reference scenario that excludes the feature, and an alternative scenario(s) that includes the feature 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).

7.3.7 Stakeholder engagement in WEF nexus and RAPs scenario planning

7.3.7.1 Co-planning of WEF nexus scenarios

One of the intrinsically complex challenges of the WEF nexus approach is the assessment of synergies and trade-offs involving multiple stakeholders with diverging views at different scales from various sectors (Karlberg *et al.*, 2015). The involvement of stakeholders who are the potential users is key in co-planning WEF nexus scenarios through the integration of expert knowledge and local knowledge (Baba *et al.*, 2018) for representing multiple perspectives, ensuring legitimacy and promoting dialogue (Martinez *et al.*, 2018; Gerlak *et al.*, 2021). Similarly, participatory scenario planning uses available knowledge beyond that of scenario developers to better target the scenarios to the user needs (van Vuuren *et al.*, 2012). However, a minority (15%) of reviewed studies confirmed that they engaged stakeholders from their study areas, while 85% did not mention involving studies. The lack of participation is a weakness in scenario planning (van Vuuren *et al.*, 2012).

The stakeholders that were engaged include think tanks (experts, academics), decision- and policy-makers (e.g. national and local governments and their respective departments and agencies), citizens (farmers, residents, users and their associations), innovators, non-governmental organizations (NGOs), charitable organizations, and private sector. Online investigations can select these, purposive sampling and snowball sampling (Kotir *et al.*, 2016; Martinez *et al.*, 2018; Geressu *et al.*, 2020). The engagement of stakeholders was through data surveys (Hussien *et al.*, 2017; Casazza *et al.*, 2021), interviews (Baba *et al.*, 2018; Bremer *et al.*, 2018; Tan and Yap, 2019), meetings (Gallagher *et al.*, 2020), workshops (Knox *et al.*, 2018; Hoolohan *et al.*, 2019; Larkin *et al.*, 2020), questionnaires (Karabulut *et al.*, 2019; Toboso-Chavero *et al.*, 2021), informal discussions (Geressu *et al.*, 2020; Siderius *et al.*, 2021), seminars (González-Rosell *et al.*, 2020), weighting WEF nexus assessment criteria (Nasr and Zahran, 2016), identifying local WEF challenges, considerations and preferences (Almulla *et al.*, 2020; Dhaubanjar *et al.*, 2021; Siderius *et al.*, 2021), selection of interventions (infrastructural plans, adaptation options) and their performance objectives/needs/metrics (Geressu *et al.*, 2020; Dhaubanjar *et al.*, 2021; Siderius *et al.*, 2021), identifying relevant policies and options or portfolios (solutions) (Knox *et al.*, 2018), validating scenarios (Karlberg *et al.*, 2015; Johnson and Karlberg, 2017; Ghafoori-Kharanagh *et al.*, 2021) and identifying gaps for future exploration (Khan *et al.*, 2020). The deliberate involvement of relevant stakeholders in the co-production of models and indicators and the interpretation of results ensure an appropriate representation of the complex WEF nexus in the human-environment system and its associated management practices and policies (Momblanch *et al.*, 2019). In practice, stakeholders assist in validating model structure, data, and results and gathering information on national (local) priority policy objectives and measures, while their validation of results renders credence to the scenario planning process and outcomes (Sušnik *et al.*, 2021).

7.3.7.2 Co-development of RAPs

All RAPs studies mentioned stakeholder engagement. Two major stakeholders participating in RAPs studies include higher-level decision-makers, experts, and farmers' communities (UNDESA, 2016). These stakeholders came from research and government departments/agencies such as statistics, agriculture, forestry, fisheries, cadastral/geographic survey, extensionists, interest groups, national policy and political leaders, environment, and meteorology). Some were from academia, including economists, agronomists, livestock experts, entomologists, soil scientists, plant pathologists, irrigation specialists, water management experts, plant breeders, climate change scientists, and social scientists. Other stakeholders were from civil society organisations (CSOs), international non-governmental organizations (INGOs), representatives of growers/farmers (cooperatives, unions), agricultural industry, commodities, and citizen groups (Ahmad *et al.*, 2015; Zubair *et al.*, 2015; Palazzo *et* *al.*, 2017). The stakeholders provided inputs on current conditions and future trends, identified research priorities, quantified key impact indicators, and co-designed locally relevant adaptation strategies and future development pathways and scenarios (Homann-Kee Tui *et al.*, 2015; Antle *et al.*, 2018b; Cammarano *et al.*, 2020).

Stakeholder engagement is integral in RAPs development for defining scenario parameters (Biewald *et al.*, 2017), developing and evaluating technological options (Antle *et al.*, 2018a; Antle and Valdivia, 2021) through the integration of scientific and local stakeholder-based knowledge in research, education, and extension (Antle *et al.*, 2017b). Their participation can reduce uncertainty in scenario results while enhancing acceptability, legitimacy, credibility, reality, clarity, reliability relevancy, and salience of RAPs to users; while facilitating ownership and strengthening the stakeholders' ability to use model outputs (Valdivia *et al.*, 2015; UNDESA, 2016; Rosenzweig *et al.*, 2021). Preferably, researchers are fully engaged in the large portion of design and implementation of RAPs which involves quantifying parameters in the future, while stakeholders should be fully engaged during action-oriented processes such as consideration of implementation of adaptation strategies (Antle *et al.*, 2017b). Thus, the time and nature of stakeholder participation depend on the researchers' objective, knowledge, and skills and the capacities of stakeholders (Antle and Valdivia, 2016; Antle *et al.*, 2017b). According to Rosenzweig *et al.* (2016), the active participation of stakeholders in the RAP processes of co-development and co-analysis is essential. It necessitates: (i) clarifying key questions, (ii) elucidating regional context, history, and development challenges, (iii) building narratives of potential change, (iv) prioritizing elements of development, intervention, and adaptation for assessment, (v) providing feedback on the validity of assumptions in scenarios and model parameters, (vi) classifying strata that help interpret patterns in distributional outcomes across households, and (vii) refining key messages for dissemination and engagement with wider audiences (UNDESA, 2016; Antle and Ray, 2020; Antle and Valdivia, 2021).

7.3.8 Roadmaps for WEF nexus and RAPs scenario planning

7.3.8.1 Roadmap for co-planning WEF nexus scenarios

A minority (approximately 8%) of the reviewed WEF nexus scenario planning studies explicitly reported their reproducible and repeatable procedures/activities roadmap. This presents a challenge due to the lack of a scenario planning blueprint for the WEF nexus community of researchers and practitioners. Out of this minority, the steps followed differed among studies, as was the case with their objectives, methods, approaches, and procedures. However, the process is iterative (Gallagher *et al.*, 2020; Khan *et al.*, 2020; Dhaubanjar *et al.*, 2021; Sušnik *et al.*, 2021) and commonly applies the story and simulation (SAS) approach in which qualitative scenarios (narratives or storylines) are developed and quantified for analysis by nexus modelling tools (Karlberg *et al.*, 2015; Keskinen *et al.*, 2015). The overarching steps include identifying and engaging stakeholders, system mapping/framing, developing qualitative scenarios, quantifying scenarios, and assessing the WEF nexus of scenarios (Johnson and Karlberg, 2017; Baba *et al.*, 2018; Marttunen *et al.*, 2019). Articulated steps and tasks and their chronology in fulfilling the overarching steps in WEF nexus scenario planning are presented by (Kotir *et al.*, 2016; González-Rosell *et al.*, 2020; Enayati *et al.*, 2021). A key scenario to be included in the 'business-as-usual' (BAU) is that all population varies temporally. At the same time, all current (or historical) resource management practices remain more or less the same, or their evolution follows historical trends (Keskinen *et al.*, 2015). This BAU scenario offers a baseline for comparison with alternative scenarios.

7.3.8.2 Roadmap for RAPs development and analysis

Valdivia *et al.* (2015) proposed an iterative process for developing context-specific RAPs, wherein the team defines a general narrative of the RAPs considering socioeconomic, biophysical, institutional, policy, socioeconomic, and technological factors and develops narratives and quantitative information for them, incorporating expertise from within the team, engaging stakeholders and recruiting outside expertise as applicable. The iteration in co-production, analysis and review of RAPs is essential for refining scenario narratives, storylines and parameters until realistic scenarios and satisfactory trade-off outcomes are achieved (Antle and Valdivia, 2016; Homann-Kee Tui *et al.*, 2021a). The RAPs development and assessment process was further elaborated by (Antle and Valdivia, 2016; Rosenzweig *et al.*, 2016; UNDESA, 2016; Valdivia *et al.*, 2021) and customized in RAPs development and assessment studies by (Tabatabaeefar *et al.*, 2009; Mitter *et al.*, 2019; Mitter *et al.*, 2020). In the generic RAPs development process and assessment, the interactions with stakeholders follow several cycles, with each cycle involving several overarching steps, including (i) defining climate risks, (ii) engaging stakeholders, (iii) co-designing pathways, (iv) co-designing adaptations and interventions, and (v) impact assessment (Homann-Kee Tui *et al.*, 2021a). The detailed tasks, workshops and meetings required to fulfil these steps are articulated by (Antle and Valdivia, 2016; Rosenzweig *et al.*, 2016; Valdivia *et al.*, 2021).

7.3.9 Summary: proposing a generic framework and roadmap for co-developing WEF nexus scenarios

To summarize, climate change and other drivers such as socioeconomic, technological and policy threaten water, energy and food security in the present and future. Thus, it is imperative to plan WEF nexus scenarios that inform decisions on present and future balanced and sustainable management and development of the WEF resources. WEF nexus scenarios representing possible future developments of anthropogenic drivers of climate change consistent with socioeconomic developments enable the assessment of possible changes in the climate system, impacts of society and ecosystems, and the effectiveness of response options, including adaptation and mitigation under a wide range of future alternative outcomes (O'Neill *et al.*, 2016). Established pathways, protocols and tools should guide the development and analysis of such WEF scenarios. Unfortunately, established individual pathways such as SSPs, RCPs, and RAPs are incomplete by design but complement each other when integratively combined and applied in individual studies where changes, risks and adaptation or mitigation strategies are assessed (O’Neill *et al.*, 2020).

In line with the preliminary findings of this literature review, we propose a generic framework for guiding the WEF nexus community in planning scenarios (Figure 7.8).

This framework is founded on the integration of WEF nexus modelling and application of SSPs, RCPs and RAPs as proposed by several WEF nexus scenario planning studies and Agricultural Model Intercomparison and Intercomparison Project (AgMIP) Regional Integrated Assessment (RIA) framework and studies (Rosenzweig *et al.*, 2016; Daher *et al.*, 2017; Tumbo *et al.*, 2020).

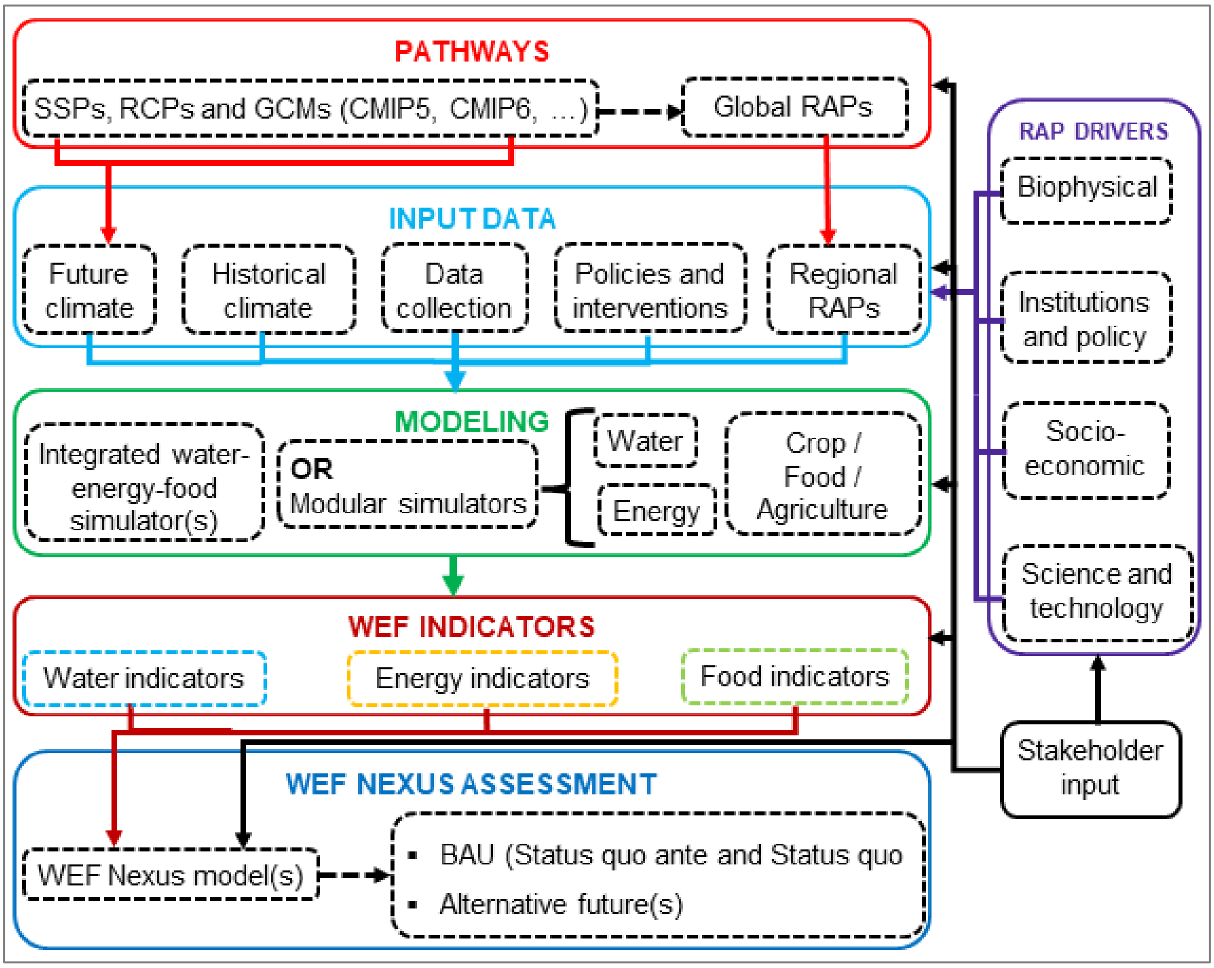


Figure 7.8: Generic framework for integrative co-planning of WEF nexus scenarios

Key features of the generic framework include stakeholder engagement, scenario drivers and pathways, input data, modelling for WEF resources, WEF nexus indicators and modelling. The framework is flexible 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 environment, land, ecosystem, biodiversity, health and economy.

Related to this generic WEF nexus scenario planning framework, we propose a generic iterative roadmap outlining key tasks and steps for integrative development and exploratory analytic modelling of scenarios from socioeconomic, climate change and agricultural evolution pathways (Figure 7.9).

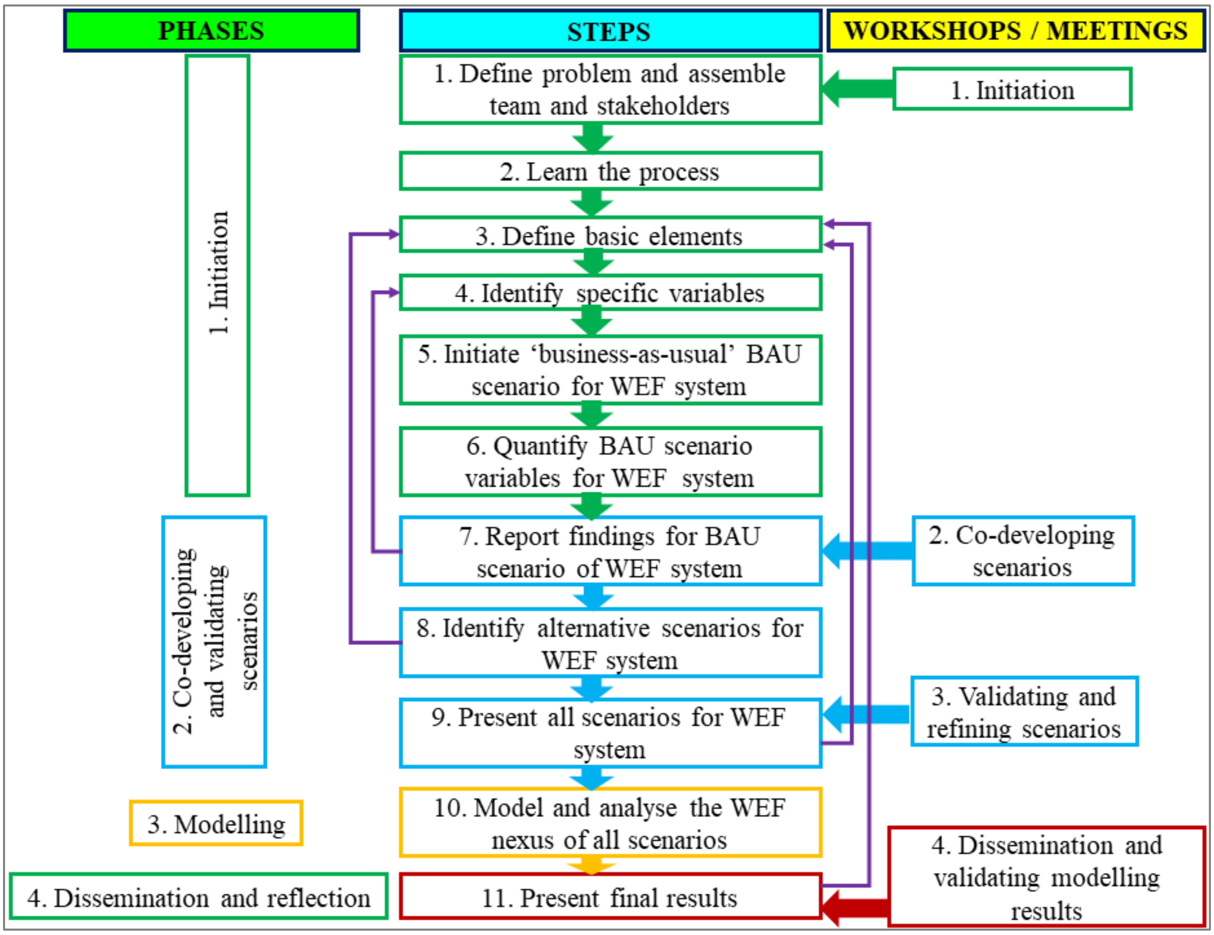


Figure 7.9: Iterative generic roadmap for integrative co-planning of WEF nexus scenarios

The proposed iterative generic roadmap for WEF nexus scenario planning consists of four phases and 11 steps that are ideally accomplished by four stakeholder workshops. The first step involves problem definition, assembling the research/implementation team and identifying stakeholders, considering the team's expertise across the relevant nexus disciplines as well as the power/influence of the stakeholders. However, the team can solicit additional expertise from external members when needed. The second step entails training the stakeholders and other team members on concepts and processes such as nexus thinking, scenario planning, pathways, and documentation/reporting templates. Stakeholders can provide feedback on initial methods and tools in this step. In the third step, basic project/study/work elements are identified and defined. These elements of analysis include spatial scales, global pathways and related assumptions (e.g. SSPs, RCPs and RAPs), and several 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 visions and Sustainable Development Goals (SDGs). Locally relevant data is also elicited from stakeholders relating to interlinkages, major sectoral and nexus challenges, objectives, perceived risks (trade-offs) and associated underlying mechanisms, regional priorities, drivers of change, key decisions and questions related to WEF security, climate and socioeconomic change, and future adaptation and mitigation. This information is critical for co-developing conceptual models through cognitive or mind-mapping of the system and sub-systems. The fourth step involves identifying specific variables, including interventions/potential actions, policies, adaptation strategies, investments, key parameters, and indicators to be included in the WEF nexus scenarios, and a process for quantifying their changes over the time horizon of the analysis.

The team and stakeholders co-develop short narratives/storylines (qualitative scenarios) for an initial BAU scenario in the fifth step, after which team members are assigned to variables, in the sixth step, for further research, quantification and documentation in the BAU WEF scenario, which they can share with experts in due course for feedback. In the seventh step, team members report findings for each variable, discuss their storylines, check their consistency and iterate (steps 4-6) until they reach a consensus. Here external researchers or invited experts may be included for independent validation. The next (eighth) step requires the identification of alternative WEF pathways, scenarios and their narratives, and they are subjected to steps 3-7 for elaboration with input from stakeholders.

In the ninth step, team members present and elaborate all WEF scenarios to the entire research/implementation team and all stakeholders for peer and stakeholder review. If feedback from stakeholders (and external researchers or invited experts) is negative, the team may repeat steps 3-8 to revise the BAU and alternative future WEF scenarios. Upon consensus, the tenth step involves modelling/simulating/optimizing and analysing the nexus of the developed WEF scenarios, analysing their sensitivity and making recommendations for the selection and prioritization of action plans, investment portfolios (including infrastructure development) and reforms for policy and governance. Here stakeholders can provide key input in the co-selection of models and data, analysing and critiquing modelling to refine data and assumptions until agreement. The final (eleventh) step entails presenting modelling results, research highlights, and key messages to the entire research/implementation team and all stakeholders (and external researchers or invited experts) for feedback, for example, on challenges or issues/priorities/questions not yet addressed. There may be a need to revise the WEF nexus scenarios by repeating steps 3-10 if feedback is negative and a consensus is not reached.

7.4 Conclusions and recommendations for science and evidence-based explorative imagination of WEF nexus in the future

Co-development through participatory planning of WEF nexus scenarios creates an opportunity for dialogue, integration of local and expert knowledge, mutual learning of involved actors and dealing with complexity and uncertainty inherent in WEF systems today and in future. Several studies applied scenario planning in the WEF nexus approach, considering major drivers of change, including climate change, socioeconomic, economic, environmental, land use and technological. Most WEF nexus scenario planning was conducted at large and medium scales, leaving a gap for local-scale applications that must be addressed. Favourably, long-term planning horizons dominated in WEF nexus scenario planning which is desirable for planning sustainable development. The tools applied for scenario planning at different spatial scales include ABM, SDM, LCA, hydrological models, hydro-economic models, crop simulation models, crop water models, and WEF nexus models. In planning WEF nexus scenarios, studies considered globally established pathways of socioeconomic evolution (SSPs) and climate change (RCPs), cross-cutting interventions, and measures for managing the supply and demand of WEF resources. The recently published CMIP6 SSP-RCP pathways received little attention in WEF nexus scenario planning. Henceforth for SSPs and RCPs, there is a need to consider these updated SSP-RCP pathways for relevance. RAPs were missing in WEF nexus scenario planning which is a drawback in imagining future agricultural development pathways within the WEF nexus approach. Hence there is potential for the inclusion of RAPs to explore integrated WEF nexus future scenarios. The major cross-cutting interventions and measures 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 major energy sector interventions and measures included (i) transition, transformation and augment 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. The major 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) change diet, lifestyle, and consumption patterns, and (viii) alternative foods. A minority of previous WEF nexus scenario planning studies reportedly involved stakeholders, further emphasising promoting this participatory practice. Stakeholders' active inclusion and participation enhance the validity and applicability of the co-developed WEF nexus scenarios.

This study uses its findings to propose a generic WEF nexus scenario planning approach and roadmap. The generic approach is stakeholder-driven and flexible to include other pertinent dimensions, while the roadmap is iterative. Future research needs to collate and synthesise insights, i.e. the impacts (or outcomes or results) of different drivers, pathways, interventions, strategies and scenarios on the future WEF nexus, from the literature on WEF nexus scenario planning. Similarly, such analysis must highlight the resultant synergies and trade-offs from adaptive and maladaptive actions, respectively. Such studies need to be done for regions demarcated on common WEF challenges as a starting point that can assist, inform and guide practitioners, decision- and policy-makers in selecting relevant WEF investment portfolios. There is a need to develop compact and user-friendly tools dedicated to WEF nexus scenario planning.

8 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

8.1 General discussion

Over the last decade, the water-energy-food (WEF) nexus has emerged a prominent contender in approaches for integrated resources management. The WEF nexus strives for the systematic understanding and management of trade-offs and synergies across the interlinked water, energy and food sectors. Southern Africa has made notable deliberates efforts to adopt and contextualise the WEF nexus concept for realising regional socio-economic development goals related to sustainable natural resources management, job and wealth creation and achieving WEF securities. The global goal of this project was to develop a water-energy-food (WEF) nexus modelling approach for the African continent, using southern Africa as a case study, that could be used to quantify and interpret the cross-sectoral complexity of resources and support the transformation required to meet the increasing demand for WEF resources in the context of climate change. To achieve this, the project sought to assess the WEF nexus in southern Africa, specifically the status, opportunities, and possible regional case studies for the WEF nexus. The project also sought to develop an applicable and scalable WEF nexus model that integrates and quantifies the relationships among the WEF sectors and assesses whether resource planning and management are sustainable or unsustainable. The model results indicate priority areas needing immediate intervention, as results provide a clear overview of current resource performance. The model would also provide for scenario planning, an assessment of the Sustainable Development Goals and rural livelihoods transformation within the context of the region's socio-economic development goals. These projective objectives were systematically achieved through a transdisciplinary process-based mixed methodology.

Existing WEF-related policies, laws, strategies and institutional arrangements are silo-based and thus limits the capacity to address socio-economic development challenges in an integrated cross-sectoral manner. Climate change amplifies the existing WEF insecurities and complicates the uncertainty for future development plans in all southern African member states. The WEF nexus approach simultaneously (i) offers opportunities to effectively achieve sustainable socio-economic development and transformation through cross-sectoral coordination and collaboration at various levels, and (ii) promotes the achievement of several nexus-relevant SDGs including SDGs 2, 6 and 7, with interlinked positive effects on several other SDGs. Water, energy and food security are somehow homogeneously key priority areas for SADC and their integrated regional planning could catalyse regional integration, achievement of socio-economic security and improving regional natural resource use efficiencies. However, this translation of the WEF nexus concept to practice need a strong foundation of political will through commitment from member states, supported by technological innovations that promote simultaneous achievement of WEF securities, environmental wellbeing and integrity of maintaining natural resources. This calls for deliberate radical drift from national sovereignty to regional integration and cooperation.

A key output of this project was the development, testing and deployment of a user-friendly, open access, web-based and GIS-enabled integrative WEF nexus analytical model, iWEF. Based on a previous AHP-based model, the iWEF model is intended to support the integrated management of WEF resources through identification of trade-offs as entry points for prioritising interventions. The iWEF model is “hard-link” integrated with GIS through open-source base maps for location of case study areas and spatial visualization of the WEF nexus. The model’s outputs include a spider graph (or radar charts or sustainability polygons) of normalised indices and maps, allowing quantification, understating and visualisation of interactions, interdependencies, and inter-connectedness among WEF nexus sectors. The quantitative indices highlight overall and specific performance of the WEF system and its sectors, respectively. The additional maps provide a visualisation of the spatial distribution of the WEF nexus and hotspots in the locations of interest. The iWEF model displays radar charts and map results for multiple case studies, allowing for scenario planning and analysis. The iWEF model targets users in academia, research, natural resource management, planning, policy- and decision-making. In this way, the iWEF model can aid in congregating different stakeholders for ancillary assessment and decision-making for the composition of informed policies and responsible investments for transformational growth. Future developments are planned so that indicators in the iWEF model can reflect both qualitative and quantitative aspects of WEF resources and broaden indicators to include additional dimensions such as environment and health. The iWEF model also needs to be further improved and strengthened for its abilities of scenario planning so that it can guide on planning, implementation and monitoring of robust nexus-friendly interventions and investments.

Based on regional-level indicators, the project also developed and applied a WEF Nexus Analytical Livelihoods Framework (ALF) for assessing the potential of the WEF nexus approach to inform rural livelihoods transformation at a regional level. It was found that current resource utilisation and management is unsustainable and undermined by trade-offs due to siloed sectoral approaches in the SADC region. For example, a dedicated focus on food security and self-sufficiency only is bound to transferring problems to other sectors, and thus undermine rural household food security and well-being. The WEF Nexus ALF proved useful in providing insights into sustainable natural resources management, building resilience and well-being in rural areas through attaining WEF securities. Thus, the WEF nexus proved to be an inclusive, transparent, intergovernmental approach for all stakeholders and a decision-support tool for informing holistic and systematic development agendas. The link between WEF and SDG indicators provides an opportunity for further studies on assessing the performance of related SDGs using the WEF nexus analytical model. Despite the gap in data availability at the household level, future studies should strive to analyse the WEF nexus at household scale for a greater impact.

SDGs are targets to be achieved by 2030 and they are monitored through measurable metrics. This project applied the WEF nexus modelling approach to assess progress towards SDGs by establishing the interlinkages between several SDGs and nexus approaches in a South African case study. These linkages facilitate sustainable natural resources management and balance cross-sectoral trade-offs and synergies. In doing so, the study highlighted pathways to simultaneously ensure socio-ecological sustainability and environmental health. Resource management remains unsustainable due to increasing poverty and hunger at the household level, water scarcity, and energy insecurity. The connectedness of current challenges (climate change, population growth, migration, and the emergence of novel infectious diseases) and their impact across multiple resources and sectors requires holistically transformative approaches that address these cross-cutting challenges. Managing the intricate relationships between distinct but interconnected sectors through nexus planning has provided decision-support tools to formulate coherent strategies that drive resilience and sustainability. The established linkages between nexus planning and SDGs could strengthen cross-sectoral collaboration, cooperative governance and management through evidence-based interventions. As food production, water provision, and energy accessibility are the major socio-economic and environmental issues currently attracting global attention; the methodology promotes attaining sustainability by 2030.

The imbalance between resource availability and demand due to population increase, among multiple drivers, requires integrative and transformative approaches to inform policy, decision-making and practice on coherent adaptation strategies for improved livelihoods and resilient communities. This project applied WEF nexus analytical model to holistically assess resource availability, distribution, use and management locally in Sakhisizwe Local Municipality, South Africa. The aim was to inform policies, decisions and practice on improving resource-poor rural communities' livelihoods. The analysis by the WEF nexus analytical model simplified the relationship between the intricately interlinked socio-ecological components and facilitated the identification of priority areas for intervention. It was found that resource management is marginally sustainable in Sakhisizwe Local Municipality and coherent interventions are needed for improving the simultaneous security of water, energy and food. The study confirmed the utility of the WEF nexus approach at a local scale for informing decisions on improving livelihoods, enhancing resource securities, identifying priority areas for intervention and providing transformative pathways towards sustainable development.

Having addressed objectives related to developing an applicable and scalable WEF nexus modelling approach and applying it at multiple scales to assess rural livelihoods and SDG performance assessment, a subsequent objective was to propose an approach for developing WEF nexus scenarios. This study adopted a systematic literature review on WEF scenario planning using the PRISMA protocol. Specifically, we focused on WEF nexus drivers of change, scales (spatial and temporal), analytic tools, pathways, stakeholder engagement and roadmaps. The application of scenario planning is uncommon in the WEF nexus approach since majority of studies focus on status quo ante and status quo. In the studies that applied scenario planning in the WEF nexus approach, they considered major drivers of change, including climate change, social, economic, environmental, land use and technological. Long-term planning horizons dominated in WEF nexus scenario planning; this is desirable for sustainable development planning. Various analytic models were applied for analysing resources and their nexus, while studies considered globally established pathways, cross-cutting interventions, and measures for managing the supply and demand of WEF resources. The common sectoral interventions considered measures for resource production/generation, supply, utilization/use and demand management, including augmenting supplies, circular economy, improving efficiency, policy and regulation, changing lifestyles, conservation, and raising awareness. The updated Coupled Model Intercomparison Project Phase 6 (CMIP6) SSP-RCP pathways need to be considered for relevance in WEF nexus scenario planning. Similarly, there is scope for including established pathways of evolution of agricultural production systems such as Representative Agricultural Pathways (RAPs) in exploring integrated WEF nexus future scenarios. Unfortunately, only a few studies reported on stakeholder engagement. The findings from the literature review also guided us to develop a generic stakeholder-driven and science-based (i) flexible integrative framework and (ii) iterative roadmap for co-planning of WEF nexus scenarios. We envisage the review, proposed framework, and roadmap to guide and inform nexus investment dialogues for planning WEF systems that are robust, resilient and sustainable across generations. Further related work need to analyse and synthesize the likely impacts of different WEF pathways and scenarios on the nexus in different regions, for potentially informing regionally differentiated and locally specific nexus-coherent strategies and interventions. Similarly, there is need to improve the scenario planning capabilities of existing WEF nexus tools such as the iWEF model.

8.2 Conclusions

The project successfully developed, tested and applied a WEF nexus modelling approach at various scales, from regional (southern Africa) to national (South Africa) and local (Sakhisizwe Municipality). This demonstrated the applicability of the WEF nexus approach and the developed WEF nexus modelling approach at various scales. Additionally, applying the WEF nexus model to assess progress towards the SDGs at national scale provided a unique opportunity to demonstrate the WEF nexus approach’s suitability for informing planning, policy and decision-making. Similarly, we demonstrated the applicability of the WEF nexus approach in informing practice at local scale.

8.3 Recommendations

The initial work on developing WEF nexus scenarios is an important milestone as it will broaden the applicability of the WEF nexus approach. The fact that WEF nexus tools do not have predictive capability restricts their application to status quo assessments and identification of areas for intervention. With the inclusion of scenarios, the iWEF model could be applied for strategic decision-making and assessing sustainability pathways. Future work should focus on improving existing WEF nexus tools such as the iWEF model, generating WEF nexus case studies for evidence, and assessing actual interventions/projects/plans. This will aid in practicalising the WEF nexus approach. In addition, the uptake and adoption of the WEF nexus approach will rely on the sufficient capacity to embed and drive the approach. A current major limitation is the lack of capacity at all levels. This should be a priority for future research for development.

9 APPENDIX I: REPORT ON RESEARCH DISSEMINATION

A. Peer-reviewed articles (Total = 20)

1. Botai, JO, Botai, CM, Ncongwane, KP, Mpandeli, S, Nhamo, L, Masinde, M, Adeola, AM, Mengistu, MG, Tazvinga, H, Murambadoro, MD, Lottering, S, Motochi, I, Hayombe, P, Zwane, NN, Wamiti, EK and Mabhaudhi, T. 2021. A Review of the Water-Energy-Food Nexus Research in Africa. Sustainability 13 (4): 1762. doi: 10.3390/su13041762
2. Kiala, Z, Jewitt, G, Senzanje, A, Mutanga, O, Dube, T and Mabhaudhi, T. 2022. Chapter 3 – EO-WEF: a Earth Observations for Water, Energy, and Food nexus geotool for spatial data visualization and generation. In: eds. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier. doi: 10.1016/B978-0-323-91223-5.00011-3
3. Liphadzi, S, Mpandeli, S, Mabhaudhi, T, Naidoo, D and Nhamo, L. 2021. The Evolution of the Water-Energy-Food Nexus as a Transformative Approach for Sustainable Development in South Africa. In: ed. Muthu, SS, The Water-Energy-Food Nexus : Concept and Assessments. Springer Singapore, Singapore. doi: 10.1007/978-981-16-0239-9_2
4. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F. 2022a. Water-Energy-Food Nexus Narratives and Resource Securities: A Global South Perspective. doi: 10.1016/C2020-0-03951-4
5. Mabhaudhi, T, Nhamo, L, Chibarabada, TP, Mabaya, G, Mpandeli, S, Liphadzi, S, Senzanje, A, Naidoo, D, Modi, AT and Chivenge, PP. 2021. Assessing Progress towards Sustainable Development Goals through Nexus Planning. Water 13 (9): 1321. doi: 10.3390/w13091321
6. Mabhaudhi, T, Nhamo, L, Mpandeli, S, Nhemachena, C, Senzanje, A, Sobratee, N, Chivenge, PP, Slotow, R, Naidoo, D, Liphadzi, S and Modi, AT. 2019. The water-energy-food nexus as a tool to transform rural livelihoods and well-being in Southern Africa. International Journal of Environmental Research and Public Health 16 (16). doi: 10.3390/ijerph16162970
7. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F. 2022b. Chapter 17 – WEF nexus narratives: toward sustainable resource security. In: eds. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier. doi: 10.1016/B978-0-323-91223-5.00009-5
8. Masia, S, Sušnik, J, Jewitt, G, Kiala, Z and Mabhaudhi, T. 2022. Chapter 6 – Transboundary WEF nexus analysis: a case study of the Songwe River Basin. In: eds. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier. doi: 10.1016/B978-0-323-91223-5.00003-4
9. Mpandeli, S, Nhamo, L, Hlahla, S, Naidoo, D, Liphadzi, S, Modi, AT and Mabhaudhi, T. 2020. Migration under Climate Change in Southern Africa: A

Nexus Planning Perspective. Sustainability 12 (11): 4722. doi: 10.3390/su12114722
10. Mpandeli, S, Nhamo, L, Senzanje, A, Jewitt, G, Modi, A, Massawe, F and Mabhaudhi, T. 2022. Chapter 1 – The water-energy-food nexus: its transition into a transformative approach. In: eds. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier. doi: 10.1016/B978-0-323-91223-5.00004-6
11. Naidoo, D, Nhamo, L, Lottering, S, Mpandeli, S, Liphadzi, S, Modi, AT, Trois, C and Mabhaudhi, T. 2021a. Transitional Pathways towards Achieving a Circular Economy in the Water, Energy, and Food Sectors. Sustainability 13 (17): 9978. doi: 10.3390/su13179978
12. Naidoo, D, Nhamo, L, Mpandeli, S, Sobratee, N, Senzanje, A, Liphadzi, S, Slotow, R, Jacobson, M, Modi, AT and Mabhaudhi, T. 2021b. Operationalising the water-energy-food nexus through the theory of change. Renewable and Sustainable Energy Reviews 149. doi: 10.1016/j.rser.2021.111416
13. Nhamo, L, Mabhaudhi, T, Mpandeli, S, Dickens, C, Nhemachena, C, Senzanje, A, Naidoo, D, Liphadzi, S and Modi, AT. 2020a. An integrative analytical model for the water-energy-food nexus: South Africa case study. Environmental Science and Policy 109 15-24. doi: 10.1016/j.envsci.2020.04.010
14. Nhamo, L, Mpandeli, S, Liphadzi, S and Mabhaudhi, T. 2022a. Securing Land and Water for Food Production through Sustainable Land Reform: A Nexus Planning Perspective. Land 11 (7): 974. doi: 10.3390/land11070974
15. Nhamo, L, Mpandeli, S, Nhamo, SP, Liphadzi, S and Mabhaudhi, T. 2022b. Chapter 11 – Enhancing sustainable human and environmental health through nexus planning. In: eds. Mabhaudhi, T, Senzanje, A, Modi, A, Jewitt, G and Massawe, F, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier. doi: 10.1016/B978-0-323-91223-5.00012-5
16. Nhamo, L, Mpandeli, S, Senzanje, A, Liphadzi, S, Naidoo, D, Modi, AT and Mabhaudhi, T. 2021a. Transitioning Toward Sustainable Development Through the Water-Energy-Food Nexus. In: Sustaining Tomorrow via Innovative Engineering. doi: 10.1142/9789811228032_0009
17. Nhamo, L, Ndlela, B, Mpandeli, S and Mabhaudhi, T. 2020b. The water-energy-food nexus as an adaptation strategy for achieving sustainable livelihoods at a local level. Sustainability (Switzerland) 12 (20): 1-16. doi: 10.3390/su12208582
18. Nhamo, L, Rwizi, L, Mpandeli, S, Botai, J, Magidi, J, Tazvinga, H, Sobratee, N, Liphadzi, S, Naidoo, D, Modi, AT, Slotow, R and Mabhaudhi, T. 2021b. Urban nexus and transformative pathways towards a resilient Gauteng City-Region, South Africa. Cities 116 103266. doi: 10.1016/j.cities.2021.103266
19. Taguta, C, Dirwai, TL, Senzanje, A, Sikka, A and Mabhaudhi, T. 2022a. Sustainable irrigation technologies: a water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare. Environmental Research Letters 17 (7): 073003. doi: 10.1088/1748-9326/ac7b39

20. Taguta, C, Senzanje, A, Kiala, Z, Malota, M and Mabhaudhi, T. 2022b. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. Frontiers in Water 4. doi: 10.3389/frwa.2022.837316

B. Other publications

- **In preparation**

Author(s)	**Title**
Cuthbert Taguta, Zolo Kiala, Tsitsi Bangira, Tinashe Lindel Dirwai, Luxon Nhamo, Aidan Senzanje, Hodson Makurira, Graham P W Jewitt, Sylvester Mpandeli, Tafadzwanashe Mabhaudhi	Introducing iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool
Cuthbert Taguta, Tinashe Lindel Dirwai, Aidan Senzanje, Hodson Makurira, Graham Jewitt, Tafadzwanashe Mabhaudhi	Co-developing Integrated Water-Energy-Food Nexus Scenarios: a systematic review of methodology
	Insights From Planning Integrated Water-Energy-Food Nexus Scenarios
Cuthbert Taguta, Tinashe Lindel Dirwai, …, Aidan Senzanje, Hodson Makurira, Graham Jewitt, Tafadzwanashe Mabhaudhi	Preliminary Evidence of WEF Nexus Implementation at Local Scales in South Africa and Zimbabwe
	Co-planning WEF Nexus Futures in South Africa and Zimbabwe

C. Book chapter

Author(s) and Year	**Title**
Tafadzwanashe Mabhaudhi, Sylvester Mpandeli, Luxon Nhamo, Vimbayi G P Chimonyo, Aidan Senzanje, Dhesigen	Emerging Water-Energy-Food Nexus Lessons, Experiences, and Opportunities in Southern Africa. In: eds. Vasel-Be-Hagh, A and Ting,

Naidoo, Stanley Liphadzi, Albert T Modi (2020)	DSK, Environmental Management of Air, Water, Agriculture, and Energy. CRC Press, Boca Raton, United States of America. https://doi.org/10.1201/9780429196607-7

D. Conferences and Webinars

Presenters	Title	Event
Aidan Senzanje, Cuthbert Taguta, Tafadzwanashe Mabhaudhi	The iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool	23rd WaterNet/WARFSA/GWP-SA Symposium on Integrated Water Resources Management for Sustainable Development in Eastern and Southern Africa 2022 (Sun City)
Cuthbert Taguta, Aidan Senzanje, Tafadzwanashe Mabhaudhi	Towards co-producing water-energy-food (WEF) nexus futures	
Cuthbert Taguta, Aidan Senzanje, Tafadzwanashe Mabhaudhi	The iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool	WEF Nexus Winter School 2022 (Pretoria)

10 APPENDIX II: CAPACITY BUILDING

Provision was made in the budget to fund three full-time students over the project's five-year period. A summary of capacity building in the is presented in the following sections.

10.1 Post-graduate capacity building

The project has exceeded the original capacity development targets. The contractual obligation was to train three MSc students. The project engaged the following postdoctoral research fellows:

- Dr VGP Chimonyo

Dr Vimbayi Chimonyo contributed to overall project coordination. She has since left UKZN and is now a Scientist at the International Center for Maize and Wheat Improvement (CIMMYT). She is also an Honorary Research Fellow at UKZN and continues to be involved in WEF Nexus research in the regions.

- Dr S Kiala

Dr Serge Kiala contributed to the development of the iWEF tool and the addition of geospatial capabilities to the model. He has since left UKZN and is now employed as a postdoctoral research fellow at the University of the Witwatersrand. He continues to be active in WEF nexus research in the region.

- Dr T Bangira

Dr Tsitsi Bangira is currently employed as a postdoctoral research fellow responsible for overseeing the WEF nexus research portfolio. Her background is in GIS and remote sensing for spatial hydrology applications. She contributed to the iWEF model development and is currently leading case studies in the Limpopo basin.

- Dr S Tsvuura

Dr Susan Tsvuura was employed as a postdoctoral research fellow responsible for developing training material and course content for the WEF nexus.

The project also enrolled the following postgraduate students:

Name: Cuthbert Taguta (PhD in Agricultural Engineering)

Title: Implementing the Water-Energy-Food (WEF) Nexus Through Tools and Scenario Planning: A case study approach for southern Africa

The global objective is to further develop iWEF into a web-based GIS-enabled model and apply it in exploring WEF scenarios and developing recommendations for WEF nexus implementation, monitoring and evaluation in southern Africa. Over and above the review of literature on the state of implementation of the WEF nexus at sub-national scales, this study will fulfil the following specific objectives:

- To assess the status of WEF nexus tools with respect to availability, format, geospatial analytical capabilities, spatial scales and case studies.
- To further develop the capabilities of the MS Excel-based integrative analytical model for the WEF nexus into a web-based and GIS-enabled application.
- To evaluate the state (status quo ante and status quo) of WEF nexus in South Africa and Zimbabwe.
- To develop the plausible scenarios of WEF nexus in South Africa and Zimbabwe and propose guidelines and recommendations for implementation of the WEF nexus.

To date, Cuthbert has completed a majority of the specific objectives and collected his research data. He is currently analysing the data for writing his thesis and completing his PhD studies.

Name: Mphatso Malota (PhD in Agricultural Engineering)

Title: Application of Water-Energy-Food Nexus tools to inform policy and decision making in the Limpopo and Songwe river basins

Research Objectives

The overall objective of this research is to assess the applicability of WEF nexus tools to inform policy and decision making in the Limpopo and Songwe river basins.

Specific objectives are:

i. To evaluate the applicability of existing EF nexus tools to inform policy and decision making at different spatial and temporal scales.

ii. To develop and analyse WEF nexus scenarios for implementation to achieve sustainable resource management in the Limpopo and Songwe river basins.

iii. To develop an application framework of a WEF nexus tool to effectively inform policy and decision making in the Limpopo and Songwe river basins.

Progress

I faced personal challenges in 2022 and I deregistered in August 2022. I am planning to re-register in June 2023. Currently, I am still refining my research proposal.

Name: Nosipho Dlamini (MSc in Agricultural Engineering)

Title: Developing Climate Change Adaptation Strategies using the Water-Energy-Food Nexus Approach: A Case Study of the Buffalo River Catchment, South Africa.

Research Objectives

The global research aim is to develop adaptation strategies which respond to climate change, using existing Water-Energy-Food (WEF) nexus tools for water supply management in the Buffalo River catchment. The specific objectives are to:

- Assess climate change impacts on surface water availability in the Buffalo River catchment, South Africa.
- Investigate and analyse the reliability of the Buffalo River catchment's water resources system in supplying irrigated agriculture and energy generation water demands under climate change.
- Apply the WEF nexus as a natural resource management tool to optimize existing climate change development plans in merging potential gaps between water demands by irrigation and energy generation, and available surface water.

Progress

To date, Nosipho has submitted her first draft, which came back with a conditional pass. She is now attending to the reviewers comments, with the aim of submitting the second draft in time for the April/May 2023 graduation ceremony.

Name: Lovemore Ntuli (MSc in Agricultural Engineering)

Title: Implementing the WEF Nexus approach within smallholder farming systems between South Africa and Zimbabwe.

Research Objectives

The overall objective of this research is to assess the implementation of the WEF nexus approach in smallholder farming systems between South Africa and Zimbabwe.

Specific objectives are:

i. To investigate the policies and governance structures for the application of the WEF nexus approach at the local scale in South Africa and Zimbabwe.

ii. To assess the WEF nexus dynamics (water and energy for food production) in selected smallholder farmers in South Africa and Zimbabwe.

iii. To evaluate how the lessons from the WEF nexus dynamics in selected smallholder farmers in South Africa and Zimbabwe can be applied to improve livelihoods.

Progress

Despite facing some registration challenges, Lovemore is currently working on the research proposal.

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