WATER-ENERGY-FOOD NEXUS AS A SUSTAINABLE APPROACH FOR ADVANCING FOOD AND NUTRITION SECURITY AND ACHIEVING SDGS 2, 6 AND 7 WITH SPECIFIC ATTENTION TO EFFICIENT ENERGY USE FOOD PRODUCTION

Report to the
WATER RESEARCH COMMISSION

prepared by

A. Senzanje[1], T. Mabhaudhi[2] and M. Mudhara[3]
[1]School of Engineering, University of KwaZulu-Natal, Pietermaritzburg
[2]Centre for Transformative Agriculture & Food Systems,
School of Agricultural, Earth & Environmental Sciences University of Agriculture,
University of KwaZulu-Natal, Pietermaritzburg
[3]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal,
Pietermaritzburg

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Obtainable from:
Water Research Commission
Bloukrans Building, 2nd Floor
Lynnwood Bridge Office Park
4 Daventry Road
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

EXECUTIVE SUMMARY

Pressure for water, food and energy is on the rise, driven by several factors, such as population growth, economic growth, urbanisation, changing lifestyles, climate change and environmental degradation. By 2030 the global population will need at least 40% more water, 35% more food and 50% more energy. By 2050, a 70% increase in global food demand is predicted. Meeting and managing the demand for water, energy, and food will require integrated efforts and understanding of tradeoffs across these systems and scales. The water-energy-food (WEF) nexus has emerged as an integrated and systematic approach in the past decade. The challenges South Africa faces concerning WEF securities make it imperative that future development be anchored in such an approach. The project's overall aim was to develop a WEF nexus framework, applicable WEF nexus model, indices and guidelines for adopting and upscaling the WEF nexus approach in South Africa with linkages to Sustainable Development Goals (SDGs) 2, 6 and 7.

The literature review focused on understanding the state-of-the-art regarding WEF nexus research in South- and southern Africa. The review highlighted that the WEF nexus is a polycentric approach, offering several advantages for sustainable natural resources management informing decision-making. However, this is premised on appropriate application and correct interpretation of the approach. Key gaps in knowledge that were identified included WEF nexus frameworks, scales of application, data availability, metrics and indices, and the availability tools and models. These gaps should be addressed to operationalise the WEF nexus. The research questions on developing a scalable WEF nexus model and its applicability at various scales have been addressed in offshoot projects funded by the Water Research Commission[1].

The status quo of the WEF nexus in South Africa is of great value, especially when developing a specific framework for the country. The WEF nexus framework proposed in this project considers the importance of livelihoods and human-wellbeing, an imminent threat to sustainable development, especially within South Africa. Current literature shows that policies, strategies and plans have not fully embraced the applicability of the WEF nexus to sustainable resource management, with some documents only referring to its existence. More research is needed involving policymakers, researchers, and stakeholders to provide a comprehensive perspective on the desirability of implementing WEF nexus thoughts in South Africa.

[1] CON2020/2021-00462 – Developing a web-based GIS-embedded WEF nexus tool. (WRC funded project; CON2019/2020-00007 – From theory to practice: developing a case study and guidelines for water–energy–food (WEF) nexus implementation in southern Africa.

Regarding selecting a model for the WEF nexus for South Africa, the study identified multiple models, tools and indices available to evaluate and quantify the WEF nexus. However, most of these tools may require modifications to apply to South Africa. A major constraint for the available models is data availability and quality; this will impact the reliability of the models. The study recommended developing a central database to compare and justify data. This will also contribute to standardised data collection and formats. These recommendations will be implemented through the ongoing Water Research Observatory, which the Water Research Commission is spearheading.

In selecting WEF nexus indicators for this research, use is made of outputs from other WRC-funded research. In this case, the two reference studies were those by Nhamo et al. (2020) and Simpson et al. (2019), which developed a set of WEF nexus indicators applicable at various spatial and temporal scales. Nhamo et al. (2020) developed indicators tied to drivers of natural resource security: availability, accessibility, self-sufficiency and productivity. The same drivers also speak to sustainability's economic, social and environmental dimensions. Although the WEF nexus indicators seem to cover the water, energy and food sectors, they are somewhat quiet on nutrition security. On the other hand, the WEF Nexus Indicators proposed by Simpson et al. (2019) include nutrition security as an important component of food security. Over and above the indicators, other indicators considered fall under health and environment and include:

- The proportion of the population using safely managed drinking water services
- The proportion of bodies of water with good ambient water quality
- Mortality rate attributed to unsafe water, sanitation, and poor hygiene
- Forest area as a proportion of the total land area
- The proportion of land that is degraded over the total land area
- Prevalence of malnutrition
- Biodiversity extent/hotspots.

The broadening of indicators for the WEF nexus is currently being explored through another WRC-funded project[2]. Thus, another major contribution of this project is the number of projects that were spun out from the research questions that emerged during this project.

Scale issues, both in space and time, are important in adopting and potential application of the WEF Nexus. The spatial scale ranges from local to regional. In a country like South Africa, the administrative spatial scales would cover local, district, municipality, provincial and national scales, and then regional if one considered the SADC region. The WEF nexus applies at all these spatial scales, although the

[2] CON2021/2022-00913 – Operationalising the water-energy-food nexus.

dynamics vary somewhat. For the temporal scale, the WEF nexus implementation can be applied in the short-, medium-, and long term, like other innovations or technologies. There are no hard and fast definitions of these time scales, but as a working example, the short-term could be up to 12 months, the medium-term up to 36 months and the long-term more than 36 months. The temporal scale goes together with the spatial scale. For example, applying the WEF nexus to the local scale would probably take much shorter than applying it at the national scale.

A main criticism to date is the low uptake or mainstreaming of the WEF nexus as a planning tool in many places, including South Africa. The WEF nexus has been contextualised and applied as a concept, a conceptual framework, an analytical framework, a discourse, a tool, an innovation and even a practice. Having identified frameworks, models, indices, and metrics for the WEF nexus and how they link to the SDGs, a key research question was on scaling WEF nexus research. In general, scaling refers to increasing the number of people benefiting from a technology or a practice. This is consistent with the goal of transitioning the WEF nexus approach from theory to practice. In the main, scaling can be vertical (up-scaling) or horizontal (out-scaling), but it can also be considered in other forms.

For the successful scaling of the WEF nexus, it is important that the requirements for scaling are fully understood and conditions created for these requirements to be met or to exist. The requirements for the up-scaling, out-scaling and deep scaling of the WEF nexus can be categorised under technical, institutional, socio-economics and physical factors. Technical factors include expertise, data, and technologies (soft and hard). Institutional factors include governance structures, laws, regulations and policies, governance processes, and power and people. Socio-economic factors include roles and responsibilities of individuals and structural units, people's resources endowment, livelihood strategies and related alternatives and incomes. Lastly, physical factors include land, water and energy resources, ecosystem goods and services and infrastructure.

Considering the various facets of applying the WEF nexus approach and its scalability, the project also considered its applicability under climate change. A case study approach was taken, considering the Buffalo River Catchment using the Water Evaluation and Planning (WEAP) model and CLEWS modelling framework for water system planning. Water resources and climate change impact assessments are useful for informing sustainable water policy framing. We adopted an integrated project approach based on the WEF nexus. This included assessing climate change impacts on water supply resources and their capability to meet the anticipated future demand of WEF sectors; the study findings confirmed the interconnections between climate change and the WEF nexus.

The project's overall aim was to develop a WEF nexus framework, applicable WEF nexus model, indices and guidelines for adopting and upscaling the WEF nexus approach in South Africa with linkages to

Sustainable Development Goals (SDGs) 2, 6 and 7. The project's broad aims and objectives were to initiate an exploratory study guiding the WEF nexus approach from theory to practice. To that end, the project successfully contributed to developing a WEF nexus framework for South Africa, building on previous work, and linking it to SDGs 2, 6 and 7. Furthermore, the project reviewed and identified useful models for assessing the WEF nexus. The work on modelling was critical as it informed two other WEF nexus projects funded by the WRC, leading to the development of a scalable, web-based, GIS-enabled and user-friendly integrated WEF nexus model. The project also broke new ground in WEF nexus assessment by applying the WEAP model within the CLEWS framework for water supply planning. This was an important demonstration of how the WEF nexus approach can be practically applied to inform real-world decisions. The project transitioned the WEF nexus from theory to practice in this regard. The project also laid a strong foundation for ongoing WRC-funded research on operationalising the WEF nexus.

Lastly, the project also initiated work on developing curricula for the WEF nexus. Initial consultations highlighted a gap in capacity in South Africa and the region. To that end, the project reviewed curricula at various universities in South Africa. The findings highlighted that there was no formal WEF nexus training or courses offered at a tertiary level. The project also contributed immensely to developing and delivering curricula for the WEF Nexus Masterclass and Winter School, which were held in 2021 and 2022. Building from these also set the stage for establishing the WEF Nexus CoE as a vehicle to address and coordinate WEF nexus capacity development in South Africa and the region. The WEF Nexus CoE will also take over the coordination of the Southern African WEF Nexus Network (SAFWEN), established in 2020. It is hoped that through these various efforts, there will be coordination and advancement in WEF nexus capacity for southern Africa.

Innovations

The following innovations were achieved during the project lifecycle:

- Application, operationalise and up/outscaling the WEF Nexus in South Africa;
- WEF Nexus application and up/outscaling;
- WEF Nexus Framework, based on an adaptation of previous frameworks;
- WEF Nexus Indices, which are linked to the SDGs; and
- WEF Nexus Model, based on an adaptation of existing models.

As previously indicated, the innovation and knowledge products from the project have already informed new and ongoing projects and contributed significantly to building coherence in the WEF nexus research body.

Recommendations

Future recommendations are to focus on the next phase of WEF nexus research, operationalising the approach and transitioning it from theory to practice. This should include the development of actual case studies, and real-world application of tools/indices/metrics developed thus far. In addition, current tools are only capable of doing status quo assessments. The climate change impacts assessment done in this study highlighted the value of scenario analysis for long-term planning. Thus, future WEF nexus research should focus on developing integrated WEF scenarios that consider climate change and other factors. This will contribute to WEF nexus operationalisation. Lastly, establishing the WEF Nexus CoE is a step in the right direction. However, it needs to be capacitated for it to play a meaningful role in setting and driving the WEF nexus research agenda for the region. There is a lot of fragmentation in research, with elements of duplication and lack of advancement. The WEF Nexus CoE could play a significant role in developing and driving a coherent and cohesive research agenda. This should be coupled with multi-level capacity development targeting individual, institutional and communities of practice.

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- Freddy Rabothata (Department of Agriculture, Land Reform and Rural Development)
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ACD	African Climate and Development Initiative
AEZ	Agro-Ecological Zoning
ANEMI	An ancient Greek term for the four winds, heralds of the four seasons
ARC	Agricultural Research Council
BFAP	Bureau for Food and Agricultural Policy
CATWOE	Client, Actor, Transformations, Worldview, Owner, Environment
CC	Climate Change
CGIAR	Consultative Group for International Agricultural Research
CHEC	Cape Higher Education Consortium
CLEWS	Climate Land-use Energy and Water Strategies
CMA	Catchment Management Agencies
CPA	Communication Pathway Approach
CSAG	Climate Systems Analysis Group
CSIR	Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
CWRR	Centre for Water Resources Research
DAFF	Department of Agriculture, Forestry and Fisheries
DAFNE	Decision Analytic Framework to explore the WEF nexus
DALRRD	Department of Agriculture, Land Reform and Rural Development
DDM	District Development Model
DEA	Data Envelopment Analysis Model
DEA	Department of Environmental Affairs
DES	Distributed Energy Systems

DMR	Department of Mineral Resources
DoE	Department of Energy
DOI	Diffusion of Innovations
DPE	Department of Public Enterprises
DPME	Department of Planning, Monitoring and Evaluation
DRC	Democratic Republic of Congo
DWS	Department of Water and Sanitation
ERC	Energy Research Centre
ExCo	Executive Council
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GEO	Group on Earth Observation
GLOBIOM	Global Biosphere Management model
GWP-SA	Global Water Partnership Southern Africa
IIASA	Institute of Internal Auditors South Africa
iWEF	integrative Analytical WEF Nexus Model
IWMI	International Water Management Institute
IWMI-SA	International Water Management Institute – Southern Africa
IWRM	Integrated Water Resources Management
KE	Knowledge Exchange
KZN	KwaZulu-Natal
LEAP	Long-range Energy Alternatives Planning
M&E	Monitoring and Evaluation
MAGIC	Model for the Assessment of Greenhouse Gas Induced Climate Change

MDGs	Millennium Development Goals
MEC	Member of the Executive Council
MESSAGE	Model for Energy Supply Systems and their General Environmental Impact
MuSAISEM	Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism
NDP	National Development Plan
NGOs	Non-Governmental Organisations
NTA	Nudge Theory Approach
NXI	Nexus City Index
PRIMA	Platform for Regional Integrated Modelling and Analysis
PTIA	Pathway to Impact Approach
QEER	Qatar Environment and Energy Research Institute
RD	Root Definition
RUNRES	Rural and Urban Nexus for Resilient Cities
RVAC	Regional Vulnerability Assessment
SADC	Southern African Development Community
SAEES	School of Agricultural, Earth and Environmental Sciences
SALGA	South African Local Government Association
SANEDI	South African National Energy Development Institute
SASOL	South African Synthetic Oil Limited
SATIM-W	South African TIMES Water energy model
SDG	Sustainable Development Goals
SEACMEQ	Southern and Eastern Africa Consortium for Monitoring and Educational Quality
SHEFS	Sustainable and Healthy Food Systems
SME	Small and Medium-sized Enterprises

SSM	Soft Systems Methodology
UCT	University of Cape Town
UFH	University of Fort Hare
UKZN	University of KwaZulu-Natal
UN	United Nations
UN-DESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environmental Programme
UOG	Unconventional Oil and Gas
WACOZA	Water and Cooperation within the Zambezi River Basin
WASH	Water, Sanitation and Hygiene
WEAP	Water, Evaluation and Planning
WEF	Water-Energy-Food
WHEN	Water-Health-Environment-Nutrition
WRC	Water Research Council
WWF	World Wildlife Fund
WWF-SA	World Wildlife Fund – South Africa
ZLD	Zero-Liquid Discharge

LIST OF UNITS

GWh	Gigawatt hour
ha	Hectares
kg	Kilograms
km^2	Square Kilometre
m^3	Cubic metres
MJ	Megajoules
mm	Millimetres
Mm^3	Million cubic metres

1 CHAPTER 1: INTRODUCTION

1.1 Introduction

Globally the demand for water, food and energy is continually increasing due to rapid population and economic growth in concert with accelerated urbanisation and changing lifestyles. It is projected that by 2030 the global population will need at least 40% more water, 35% more food and 50% more energy. By 2050, a 70% increase in global food demand is predicted. Meeting the demand for food in sufficient quantities and acceptable nutritious quality underlines the importance of greater efficiencies in agricultural production systems globally (using water and energy). It is projected that by 2025, 40% of the global population will be prone to severe water stress. According to the UN SDG report 2018, water insecurity remains high and accelerated progress is needed to meet the Sustainable Development Goals (SDGs) 2 (zero hunger) and 6 (clean water and sanitation). Global energy demand is projected to rise by 25% until 2040, hence putting into doubt the attainment of SDG 7 (affordable and clean energy).

In the past decade or so, the water-energy-food (WEF) nexus has emerged as an increasingly prominent global policy, governance and research agenda (Allouche, 2011; Middleton et al., 2015). Conceptually, the WEF nexus means that water security, energy security and food security are inextricably linked and, more importantly, actions in any one sector will impact in one or both of the others. During the late 2000s and early 2010s, the WEF nexus emerged as an integral approach to sustainably manage these three resource sectors, following the convergence of ideas from various political events, academic research and reports, as well as policy papers. However, before discussing the WEF nexus concept, it is essential from a South African perspective to contextualise the research problem or put into perspective the issues that would call upon the application of the WEF nexus as a tool to solve the said problems.

It is not in contention that South Africa is a water-scarce country. South Africa is one of the 30 driest countries in the world, with an average annual precipitation of 450 mm, which is a little more than half of the world average of 860 mm (Kohler, 2016; Cai et al., 2017). Only 3% of South Africa's land surface is moderate to high potential arable land, and 1.3 million ha is under irrigation (Republic of South Africa Department of Government Communication and Information System (GCIS), 2011)). As water is both physically and economically scarce across major sectors such as energy and mining, there have been water, energy and food insecurities in the country in the recent past (Pereira, 2014). This scarcity is mainly related to water for energy and food production (including irrigation), but increasingly also for drinking and domestic purposes. Most of the challenges around access are related to the limited water infrastructural development in rural areas, affecting mostly smallholder farmers (Nhamo and Chilonda, 2012). It also needs to be noted that agriculture in South Africa is one of the key strategic sectors contributing approximately 3.2% towards the Gross Domestic Product (GDP) (Baleta and Pegram, 2014). Furthermore, the majority of people in South Africa rely heavily on agriculture for food, income generation and employment (Mugambiwa and Tirivangasi, 2017). Low availability of water of acceptable quality is the most limiting factor for agricultural production (Blignaut et al., 2009).

Further to the issue of water scarcity, other vagaries such as climate change and climate variability are set to play havoc with the water equation, and consequently energy, food and health security, in South Africa (Lobell et al., 2008; Schlenker and Lobell, 2010). South Africa has been facing severe challenges relating to water, energy and food insecurity in recent years due to the recurrence of extreme weather events such as droughts, floods, and the outbreaks of wildfires. The 2015/16 El Niño event induced an extreme drought that affected the whole southern Africa region, and South Africa experienced severe challenges with water, energy and food supply (Regional Indicative Strategic Development Plan (RISDP), 2015). Due to that drought, the nation experienced incessant power blackouts, increased in food prices and a water scarcity situation that manifested in acute water shortages experienced in the Western Cape Province, resulting in severe water restrictions. In nominal terms, 50% of South Africans do not have enough food, 98% of the country's water supply is already allocated, and the country has been experiencing instability in the energy sector, i.e. load shedding, lack of funds for maintenance and high voltage supply to industry (Von Bormann and Gulati, 2014). It becomes almost evident that meeting the SDGs, especially the SDGs 2 (zero hunger), 6 (clean water and sanitation), 7 (affordable and clean energy), and to a certain extent 15 (life on land), is going to be problematic if water, energy and food security are not dealt with comprehensively and holistically.

Water, energy and food security form the basis of a resilient economy (Von Bormann and Gulati, 2014) and sustainable and inclusive development for South Africa. The challenges of resource scarcity are pushing for the adoption of the WEF nexus in order to promote sustainable development. Currently, frameworks (institutions, policies and strategies) are developed without adequate consideration for the cross-sectoral consequences, and without considering national targets as part of the SDGs (Mpandeli et al., 2018; Simpson et al., 2019). Lack of synergy between WEF sector role players creates a gap between sectors in terms of demand, supply and implementation. For example, in South Africa, SDGs 2, 6 and 7 are directly linked, and achieving them depends on the sustainable use, access and management of WEF resources (Nhamo et al., 2019). There is a need for government sectors to move towards policy convergence in order to minimise duplication of activities, create inter-sectoral linkages at technical, policy and political levels. Cross-sectoral impacts and inter-sectoral linkages need to be considered when formulating policies, strategies and plans within the water, energy and agriculture sectors. In addition, these sectors should strive towards communicating such policies, strategies and plans in a transparent manner as well as to cross-reference their decisions. In this regard, understanding the complex relationships of the WEF nexus has become critical to the development of a sustainable and secure future for South Africa (Gulati et al., 2013).

The challenges that South Africa is facing with respect to water, energy and food securities make it imperative that future development be anchored in WEF nexus approaches. The key drivers of these challenges include: (i) increased energy demand to satisfy the country's economic development goals, (ii) rapid population growth, coupled with increased urban migration leading to a need for more food production, (iii) increased physical water scarcity problems into the future being fuelled by climate change, (iv) planned irrigation expansion as a tool for rural development, coupled with the concomitant increased demand for water for agriculture, and (v) the politically explosive poverty-unemployment-inequality nexus bedevilling the country.

1.2 WEF nexus as a research tool

Water, energy, food and other land-based resources form an intricate web where resource use and availability rely heavily on each other (Pardoe et al., 2018). In reality the WEF nexus can be viewed in the following complex interactive relationships (Zhang et al., 2018); (i) water for food – in excess of 70% of global freshwater withdrawal goes to food production, (ii) water for energy – water is needed for energy extraction, electricity generation, refining and processing in the energy sector, (iii) water for energy and food – hydropower generation exhibits energy-water-food-environment connectivity, (iv) agriculture and land for energy and water – agriculture has a dual role as an energy user and supplier in the form of bioenergy, and furthermore, agriculture production impacts the water sector through its effects on land condition, runoff, groundwater discharge, water quality, and land/water availability for other purposes, (v) agriculture, water and the environment – over-abstraction from surface water affects the minimum environmental flow that is required to maintain ecosystem services, (vi) energy for food and water – directly or indirectly, for transportation, processing, packaging, and so on, and (vii) energy for water supply and sanitation services – including activities such water pumping, water distribution networks, water and wastewater treatment, and the like. These interactions can be incredibly complex, be multidirectional and very difficult to quantify, both in space and time.

Since 2011, many actors have investigated the WEF nexus, each approaching the analyses from particular point of view, be they political, social, or scientific perspectives. Unlike Integrated Water Resource Management (IWRM), which is water-centric in nature, the goal of the WEF nexus is to approach resource management more holistically by utilising a multi- or poly-centric philosophy. Each resource sector within this nexus has an equal weighting. The WEF nexus presents an opportunity for policymakers, researchers and development agencies to integrate the sectors in order to optimise the use of the resource base, maximise synergies and minimise trade-offs and conflicts. Developing countries, such as South Africa, are likely to benefit significantly from the integrated resource management approach that the WEF nexus provides, particularly those experiencing significant trade-offs between water, energy and food. The WEF nexus provides the opportunity to move beyond the current sectoral approach to policy-making, to highlighting the interlinkages between the sectors and the need to implement a system thinking to achieve the SDGs. In recent years, a substantial amount of research effort has been directed toward exploring the WEF nexus approach from different perspectives and these included; calculation of resource flows and their interdependencies, technology assessment and policy applications, and quantifying system performance (Zhang et al., 2018). A sizeable amount of literature discusses the WEF nexus in terms of the concept, simulation tools, governance, and implementation (Zhang et al., 2018).

The WEF nexus has been applied in various contexts worldwide, and this makes it applicable for addressing the water, energy and food insecurities issues in South Africa. Food and Agricultural Organisation of the United Nations (FAO, 2014) applied the WEF nexus as; a conceptual framework for natural resources governance, a tool for decision support systems (DSS), a perspective to resource management, an analytical approach for solution-seeking in natural resource management, a conceptual framework for political analysis, and as a web-based tool for management decisions. A number of lessons have been learnt and issues flagged with respect to the WEF nexus in the region and these include; fragmented sectoral management approaches, the need for a change in thinking and governance regarding natural resources, lack of data and analytical tools for nexus DSS, the need for continuous interactions among sectors, that there are several initiatives in Africa, and there is need for linkages among these to maximise benefits, water is key link to food, energy and environmental sustainability, and that the nexus approach varies by scale.

The success in applying and managing the WEF nexus depends on several factors. Firstly, and importantly, the challenge is on all practitioners to adopt ‘inclusive and sustainable’ approaches in managing water, energy and food production – inclusive meaning involving private and public sectors, and sustainable referring to not violating environmental requirements. Next, the nexus must be applied in an integrated approach (proper and integrative), i.e. considering all essential factors or issues, highlighting the significance of certain solutions (e.g. payment for ecosystem goods and services), downplay the appropriateness of others (e.g. biofuel production from food crops). Third, it is imperative to define and quantify the interconnectedness between water, energy and food for use in policy and planning. Fourth, there is a need for easy to use WEF nexus tools, with requisite data, for all to use for policy and planning, i.e. comprehensive, inclusive and multi-scale nexus tools (e.g. WEF Nexus Tool 2.0). Lastly, there is a need for data that is good in quantity and quality and also in space and time.

The WEF nexus, as research and the operational tool, offers several advantages compared to other approaches. These advantages include; (i) achieving goals in a sector through targeted interventions in another sector, (ii) filling in knowledge gaps, promoting new technologies and generating cross-sectoral data, (iii) enabling policymakers to think of trade-offs, synergies and impacts of their decisions, (iv) promoting coordination of activities and hence integrated resources management, (v) promoting involvement of all key stakeholders, (vi) promoting sharing of experiences and learning from best practices, and more importantly (vii) promoting optimal, efficient and productive utilization of natural resources. The WEF nexus has limitations or disadvantages, and these include; requisite data to operationalise the WEF nexus may not be available (in quantity and quality), it is not always possible to identify interactions on a quantifiable basis, and the success of the WEF nexus depends, to a large extent, on the will of decision-makers.

1.3 Potential application of the WEF nexus in South Africa

The WEF nexus can be applied at two levels, i.e. technical or policy level..2

Technical: Most WEF nexus research in South Africa has focused on policy implications and opportunities, with minimal investigations into the technical aspect of the WEF nexus. In general, South Africa has much potential for renewable energy, particularly solar power generation. Green technology and infrastructure, which include recycling, renewable energy usage and sustainable building designs, will also influence resource availability in South Africa by reducing environmental pollution and improving the energy efficiency of households and businesses (Shahbaz et al., 2013). General opportunities that could enhance the evolution of the WEF nexus in South Africa include increasing resource productivity (rainwater harvesting, solar pumping, harvesting of invasive plants for bioenergy, desalination with renewable energy, applications of biotechnology), maintaining/managing natural ecosystems, and restoring (as far as reasonably achievable) degraded ecosystems, integrating poverty alleviation with green growth, and capacity building and awareness-raising (Kearney, 2010). On a technical level, there is much potential for improving data collection, as well as the documenting, visualising and sharing thereof (Nhamo et al., 2018). At a regional and national level, further studies and statistics on water demand are required.

Policy level: The most important application of the WEF nexus in South Africa is that its principles provide the opportunity to integrate the sectors so that issues may be resolved from a transdisciplinary perspective. An understanding of the interconnections of the water, energy and food sectors is critical for the development of a framework that connects all these sectors. The WEF nexus presents the opportunity for policymakers to assess the coherence of current water-, energy-, food- and climate policies, to ensure that the policies are interlinked and do not contradict one another. There is scope for improvement from management and for information and interest to be generated at a technical level. Work is also required to present the WEF nexus better at a regional level with appropriate institutional strategies to tackle the interlinked challenges with particular focus on food and water at a regional level (Schreiner and Baleta, 2015). Systems thinking is required given the complexity of the nexus, but it is not easily translated into government policy-making processes (Bazilian et al., 2011). Given this, it is critical to include policymakers and researchers when revising or developing WEF nexus policies. Those involved in policymaking processes need to keep in mind the adverse effects that climate change could have, and the implications thereof, on the WEF nexus (Carter and Gulati, 2014). Policy actions required need to simultaneously address the challenges of climate change, sustainable natural resource management, energy access, the improving agricultural productivity, and supporting investments in technologies for improving water productivity and agricultural energy use-efficiency (Carter and Gulati, 2014; Simpson et al., 2019).

1.4 WEF Nexus and the Sustainable Development Goals (SDGs) in South Africa

The following research questions arise with respect to the WEF nexus, SDGs and efficient energy use in food production in South Africa:

- How best can the WEF nexus be applied in the context of South Africa's problems?
- What policy and economic instruments are required to operationalize the WEF nexus in South Africa?
- What is the best spatial scale to apply the WEF nexus for maximum impact in South Africa – nationally, provincial, locally or all scales? And what would be the ideal case studies for the WEF nexus for South Africa?
- Is there scope for up-scaling and out-scaling the WEF nexus in South Africa?
- What is a practical temporal scale to apply the WEF nexus for maximum impact for a given spatial scale?
- What indices are required or need to be developed for sustainable implementation of the WEF nexus in South Africa?
- What WEF nexus tool(s) or model(s) apply to South Africa to quantify impacts of the WEF nexus, and what are the data and user requirements?
- How can WEF nexus move from theory to analysis to practice in South Africa?

- There exist numerous WEF nexus frameworks worldwide, which ones are more appropriate for South Africa and is there a need to develop a new one or modify an existing one?
- Is the data required for WEF nexus analysis and implementation available? If so, in what form, were and how much, and if not, where and how can the required data be realised?
- How can the WEF nexus be packaged and applied to realise the SDGs 2, 6 and 7 in South Africa? And what tools and metrics would be required for this?
- Climate change is a major factor to contend with in the WEF nexus, its impact on resource access and utilisation at various spatial and temporal scales need to be quantified in WEF nexus.
- Are there any tertiary institutions in South Africa teaching the WEF nexus, as was the case with the IWRM concept and practice? And if so, at what level and in what context?

1.5 Research Objectives

With the above research questions and activities taking place in South Africa and the SADC region, the overall goal of the research project is "*To develop a WEF nexus framework, applicable WEF nexus model, indices and guidelines for the adoption and upscaling of the WEF nexus approach in South Africa with linkages to SDGs 2, 6 and 7"*.

To achieve the overall research objective, the accompanying specific research objectives of the project are:

i. To develop or generate a usable WEF nexus framework for South Africa for the purpose of applying to the planning, development and management of water, energy and food security sectors in a sustainable manner to meet the applicable SDGs.
ii. To develop or select a WEF nexus model for South Africa to apply in studying and understanding the mass and energy flows for the various trade-offs in the use of water and energy for food and nutrition security.
iii. To identify and develop applicable metrics and indices for the WEF nexus for South Africa to be able to measure or quantify the success of applying the WEF nexus in resources management for food and nutrition security.
iv. To develop a blue-print for packaging the WEF nexus so as to realise SDGs 2, 6 and 7 for South Africa.
v. To analyse and develop modalities for upscaling and outscaling the WEF nexus in South Africa to maximise benefits that can be derived.
vi. To assess the impacts of climate change on WEF nexus in South Africa and how to best manage these impacts.

vii. To document and package (manuals, technical briefs, models, etc.) the WEF nexus materials in usable formats for the South African context. The short to medium term objective being to make WEF nexus more available and user-friendly to the different sectors of South Africa.

viii. To promote the pilot teaching of the WEF nexus in tertiary institutions in South Africa.

The research will be undertaken at different scales in South Africa, and these include at the national, provincial and local levels. National level analyses will be looking at the totality of the WEF nexus application across the water and energy sectors in the South for national food and nutrition security and efficient use of energy. It is planned that the national level analyses will link to regional WEF nexus considerations by the SADC region (although that analysis will not be done since there is already a WEF nexus programme at SADC level). The provincial-level analyses will be looking at applying the WEF nexus in a given province, e.g. KwaZulu-Natal, based on the water and energy dynamics and food production. Since water is a key, the analyses could also be undertaken at the catchment level. The local level analyses will look at specific case studies of water and energy for food production and nutrition security. By its very nature, the research will need to be iterative, for example, a WEF nexus framework is required to guide WEF nexus models and metrics, but the models and metrics must also guide the framework given the required and available data and resources to operationalise the framework and vice versa.

The scope of the project, in brief, is defined by the research objective or goal, the expected deliverables, the activities and tasks in the work packages, any constraints faced and specific exclusions as well as assumptions at the start of the project. The overall objective of the project, as stated above, is to develop a framework, develop or adapt a model, select indices and indicators and guidelines for the adoption and upscaling of the WEF nexus as a resource management tool in South Africa. The expected deliverables include a WEF nexus framework, WEF nexus model, indicators and guidelines for upscaling the WEF nexus in South Africa. This will be achieved through eight work pages broken down into specific activities to answer specific research objectives. All these will be achieved within the expected time and resources constraints. The research project assumed normal research conditions, but there was the Covid-19 outbreak in the second year of the project, and subsequent lockdowns. The lockdowns impacted the project research methods but not the expected deliverables. To achieve the last objectives, the project teamed up with other institutions to develop and run WEF nexus short courses, both virtually and practically, attended by students from various countries.

This research project is cognisant of the several WEF nexus research initiatives that are taking place in the SADC region as well as South Africa, and even sub-Saharan Africa. The research approach will aim to seek synergies with these, add value and still satisfy contractual obligations.

1.6 Final Report Layout

The final report follows the WRC format for final report, but in terms of organisation, the report is laid out in line with the above stated specific objectives. The first chapter lays out the scene and scope of the problem at hand, which is basically to understand and operationalise the WEF nexus in South as a natural resources management tool to ensure securities with respect to water, energy, food and ecosystems. The chapter culminates in defining the pertinent research questions and hence stating the applicable research objectives to answer these questions. Chapter 2 gives a broad overview of the literature reviewed on the WEF nexus, the potential application and utility of the WEF nexus in South Africa, the challenges to applying the WEF nexus, the WEF nexus and intersectoral planning in South Africa, the WEF Nexus and the SDGs and finally WEF nexus research gaps. It should be emphasised that since the research commenced, a substantial amount of research has been undertaken worldwide on the WEF nexus, there actually has been an exponential growth in WEF nexus literature since then. Chapter 3 provides an outline of the general research methodologies applied in the research project in terms of frameworks, indices, metrics, data requirements and issues of scale. Chapter 4 addresses the first specific research objective on developing a useable WEF nexus framework for South Africa. The second research objectives on developing or selecting WEF nexus model is covered in Chapter 5.

Chapter 6 deals with the issue of applicable metrics and indices for the WEF nexus in relation to SDGs 2, 6 and 7. Chapter 7 touches on the aspects of developing a blue-print for packaging the WEF nexus to realise SDGs 2, 6 and 7 at the local, provincial and national levels. The all-important concern on the modalities for upscaling and outscaling of the WEF nexus in South Africa are dealt with in Chapter 8. The chapter also covers the critical requirements for upscaling and outscaling the WEF nexus and touches on how and where to house the WEF nexus within South African institutions. Chapter 9 covers the assessment of the impact of climate change and climate variability on the WEF nexus in South Africa. The chapter also delves into how the WEF nexus can be used as a tool for natural resources management to mitigate climate change, using the Buffalo River catchment as a case study. Chapter 10 gives examples of the documentation and packaging of WEF nexus materials, both for training and as policy briefs. The last chapter summarises and concludes the report and provide recommendations going forward with regard to the WEF nexus and its operationalisation.

It's worth noting that since this research project started quite a number of related WEF nexus research projects have been spawned, some of which try to cover gaps not covered by this particular research. The new research project deal with WEF nexus is all aspects, from conceptualisation to operationalisation, from theory to practice, in space and in time, from the ground up to policy issues.

Consequently, any avid follower of the research on the WEF nexus is encouraged to also follow up on these other research activities.

Finally, it should be noted that the research project achieved all the set research objectives.

2 CHAPTER 2: LITERATURE REVIEW ON THE WEF NEXUS

2.1 A Brief History of the WEF Nexus

The demand for natural resources, particularly water and energy, increases rapidly with economic and population growth (Mabhaudhi et al., 2018). The Water-Energy-Food (WEF) nexus is the field of study used to explain the integration of resources and their interactions. The WEF nexus surfaced as a framework to sustainably manage the three components in the late 2000s. This integration began to appeal globally at the Bonn 2011 Nexus Conference (Gulati et al., 2013). It was established that the WEF nexus promotes growth through the integrated use and management of resources (Hoff, 2011). The nexus serves as a discourse, analytical tool or conceptual framework (Albrecht, 2018). Since 2011 several research institutions in South Africa; University of KwaZulu Natal, Zambezi Watercourse Commission, the University of Cape Town, and University of Stellenbosch, have investigated the framework.

The possibility of the achievement of sustainable food security is possible through cautious and integrated policy implementation in the WEF nexus (Fader et al., 2018). As in developing countries, most especially sub-Saharan Africa, poverty and food insecurity reduction are vital policy goals (Sinyolo et al., 2014). Developing policies that support the sustainability of water, energy, and food resources while concurrently achieving accessibility of the resources to all levels of society is a challenge (Simpson and Jewitt, 2019). The relatively poor households find it always challenging to access resources, constraints include but not limited to, affordability, and availability.

There is a scheme in Mutare District which is characterised as the most integrated scheme in Zimbabwe. They have an 80KW micro-hydro power project which generates energy for cold storage facilities to keep produce fresh and equipment to pump water for irrigation, to manage the water usage the community decided that the hydropower plant must be switched off for short periods (Pittock et al., 2015). Along the Mekong River basin which runs through China, Vietnam, Cambodia, Myanmar, Laos and Thailand it was observed that the development of large hydropower causes displacement of food supplies and ecological impacts (Pittock et al., 2015). This is due to large-scale hydropower using considerable amounts of water, which can be utilised for food production. In the Mekong basin, the extensive growth of hydropower supply is one of the causes of the reduction in fish diversity and quantity including the availability of water to downstream users (Smajgl et al., 2016).

Tälle et al. (2019) undertook a systematic literature review to identify resource distribution and recycling logistics in food production systems. The findings showed Synergies between interventions of sustainability in food production and energy efficiency. Trade-offs were identified between prioritising animal grazing and preserving biodiversity. Moreover Hua et al. (2019) Evaluated consumption of water resources in food and energy production in different regions and assessment of the competition for water resources in food and energy production in China, this was done by Calculating blue and green water footprints for energy and food production through the analysis of water resource competition intensity index. In the 31 provinces assessed it was established that 19 provinces with weak competition, six provinces with the medium competition, one province with intense competition, and five provinces with serious competition.

Wolde et al. (2020) Examined perceptions of the local community of WEF resources and their livelihood contributions in Ethiopia. The study utilised Binary logistic regressions and Pearson correlation coefficient to illustrate the relationship between livelihood indicators and the WEF system. The findings illustrated that perceptions of WEF are based on the benefits of singular resources rather than their interlinkages. Food was found to be the centric resource for the community. Furthermore, the study established a lack of understanding of WEF resource use and management. Consequently, Issues of food security were found to be dependent on unanticipated changes in natural resources and the physical environment, which affected socio-economic conditions.

Mnguni et al. (2020) Investigated how poor urban experience the synergies and disconnections found at the urban WEF nexus in Uganda, through observation, interviews, focus group discussions, and vision-building workshop. The results showed that most household-level vulnerabilities relate to energy poverty. Households scale back on water treatment practices such as boiling and the cooking of highly nutritious yet energy-demanding foods such as beans in efforts to conserve charcoal. This could lead to households being nutrition insecure due to energy poverty. Dargin et al. (2020) attested that comprehending the relationship between FEW, urban attributes and disasters is vital for the basis of planning resilient cities.

2.2 Status of the WEF Nexus in South Africa

In a study by Simpson et al. (2020) which focused on 21 WEF indicators in order to calculate the WEF nexus index in 170 countries. South Africa has an index of 56.1 and ranks 72nd, this index was a result of South Africa ranking highly on food-access and water-access sub-pillars while performing relatively poor in terms of the food-availability and water-availability sub-pillars. The ongoing quest of fossil fuel-based energy in South Africa is menacing food security (Simpson and Jewitt, 2019) since most energy is derived from coal, this is a challenge since inland freshwater sources and some of the most arable land overlaps with areas of coal deposits (Ololade et al., 2017). In Mpumalanga, the advancement of coal mines is detrimental to the WEF synergy as the extraction of resources affects the local quality and availability of water, which results to agriculture negatively affected (Ololade et al., 2017). The effects on agriculture will be worse as water is used for energy generation instead of food crops.

2.3 Potential Application and Utility of the WEF Nexus in South Africa

2.3.1 WEF Nexus Projects in South Africa

The WEF nexus landscape in South Africa has developed rapidly since 2011, with several research institutions undertaking related work as listed below. This is considered synergistic and complementary to our project.

i) DAFNE Project being led by Jonathan Lautze, IWMI. The overall objective is to establish a decision analytical framework for participatory and integrated planning.
ii) GWP-SA WEF nexus project Phase 1 focusing on developing a WEF nexus governance framework, and an appraisal tool for evaluating project feasibility for the WEF nexus.
iii) The University of Cape Town has a WRC-funded project focusing on generating evidence for the WEF nexus at a local scale. It is focusing on catchment and household level analyses.
iv) University of Stellenbosch is in the process of developing WEF nexus proposals focusing on the Western Cape and Cape Town, in particular, a city WEF nexus study. These are in development.
v) Jones and Wagener have just completed a WRC-funded project on developing a composite index for analysing the WEF nexus.
vi) UKZN has completed a WEF nexus assessment study for South Africa, and is currently undertaking a new WRC-funded project, as well as looking at WEF nexus research in food systems through the Sustainable and Healthy Food Systems (SHEFS) programme.
vii) UKZN also has a new project called Rural and Urban Nexus for Resilient Cities (RUNRES), which focuses on applying nexus approaches for promoting transition to a circular approach.
viii) ZAMCOM has 2 WEF nexus projects.

2.4 Challenges to Applying the WEF Nexus in South Africa

Key challenges still remained in terms of transitioning the WEF nexus approach from being a theoretical concept to a more practical evidence-based decision making/informing approach. Such transition would be highly depended on progress being made with regards to WEF nexus analytical models/tools and development of indices or metrics for quantifying WEF nexus performance. These would need to be mainstreamed into relevant national bodies and processes. Key to this process would be resolving the issue of scale – where does it make the most financial sense to implement WEF nexus type interventions, with the greatest benefits to society?

2.5 WEF Nexus and Intersectoral Planning in South Africa

2.5.1 National

Most information that can be applied to the WEF nexus in South Africa is sector-specific, but still provides essential knowledge from which the WEF nexus can be analysed. In 2014, the WWF-SA published a series of documents under the title *Understanding the Food Energy Water Nexus*, which was funded by the British High Commission in Pretoria. This series approached the WEF nexus from various disciplines' perspectives, investigating its relation to climate change, waste management, financial flows, and the integrated planning of the WEF nexus elements (Carter and Gulati, 2014). As such, these documents have contributed significantly to the current knowledge of the WEF nexus in South Africa.

The WEF nexus is currently being investigated by several universities and institutions in South Africa, with the most prominent being the University of KwaZulu-Natal (UKZN) and the University of Cape Town (UCT). Current projects are presented in Table 2.1, and a list of national WEF nexus research "champions" is provided in Appendix 1.

Concerning energy, South Africa is currently taking advantage of its geographical location in developing renewable energy generation projects (Figure 2.1). Wind-power generation and photovoltaic energy conversion are currently the most prevalent renewable energy projects, with remarkably few concentrated solar power (CSP) and photovoltaic energy projects in the southern portion of the Northern Cape. Energy generated using biomass is required to be rainfed and not utilise irrigation (Nhamo et al., 2018).

Table 2.1 WEF nexus projects, as identified in 2018.

Project	Project leader	Funded by	Commenced
Exploring the Evidence of Water-Energy-Food Nexus Linkages to Sustainable Local Livelihoods and Wellbeing in South Africa	In collaboration: ACDI (UCT), RVAC (UFH), and CWRR (UKZN)	WRC	2017
The Food, Energy, Water, Land and Biodiversity (FEWLB) Nexus project	UCT	British High Commission and the Cape Higher Education Consortium (CHEC).	2013
DAFNE	International Water Management Institute (IWMI)	European Union	2017

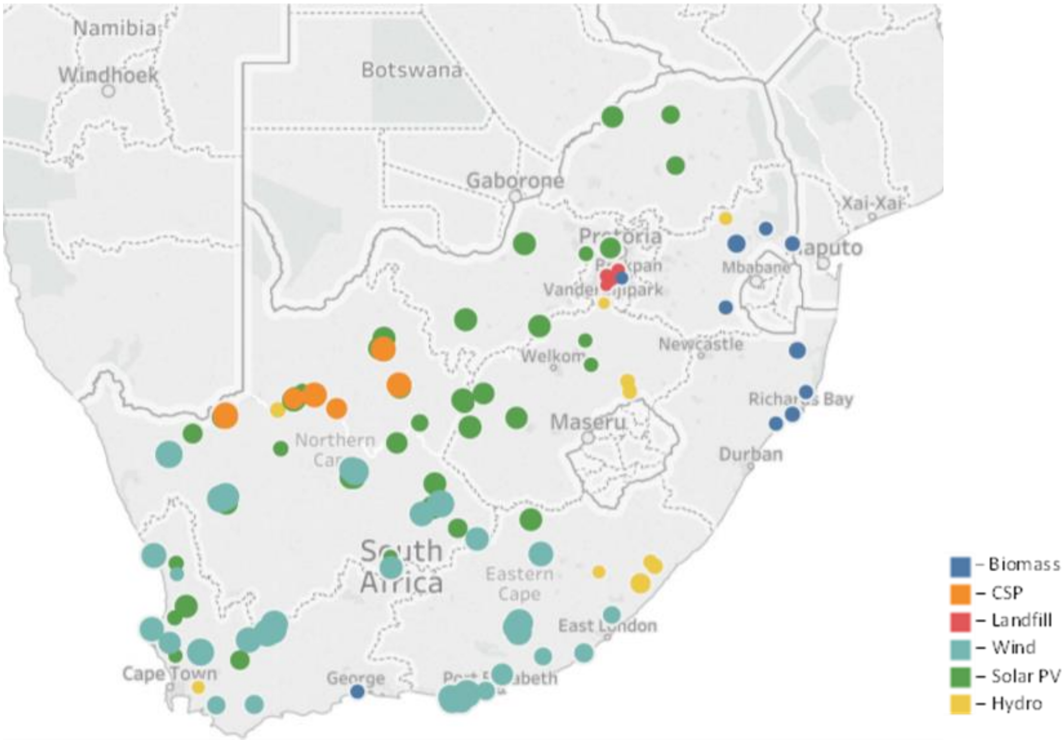

Figure 2.1 Renewable energy projects in South Africa, as at 2018 (REDIS, 2018)

South Africans are responsible for the generation of significant amounts of waste. Food waste can add up to a financial loss of R21.7 billion per annum, accounting for costs of lost food sources and disposal of food waste (Nahman et al., 2012). Approximately 90% of waste generated by South Africans is disposed of in landfill sites, with only seven years' worth of landfill waste disposal space still available (DEA, 2012). Recycling, reusing and reducing waste will become central to the WEF nexus as it relates directly to all components within the nexus. Nationally, South Africa is one of the most advanced countries in terms of achieving the targets set in the three relevant SDGs (i.e. 2, 6 and 7). Figure 2.2 illustrates the change in WEF nexus elements since 1999 in South Africa, showing a definite decrease in food-deficit over time, and a positive trend for improved sanitation facilities as well as access to improved access to both improved water sources and electricity. Simpson and Berchner (2017) stated that South Africa is currently self-sufficient with regards to cereal production, that the prevalence of undernourishment is low (less than 5% of the population), and that most of the population had access to clean and safe drinking water sources (in 2015, 93.2% of the population has access to improved water sources) and reliable electricity (in 2014, 86% of the population had access to electricity).

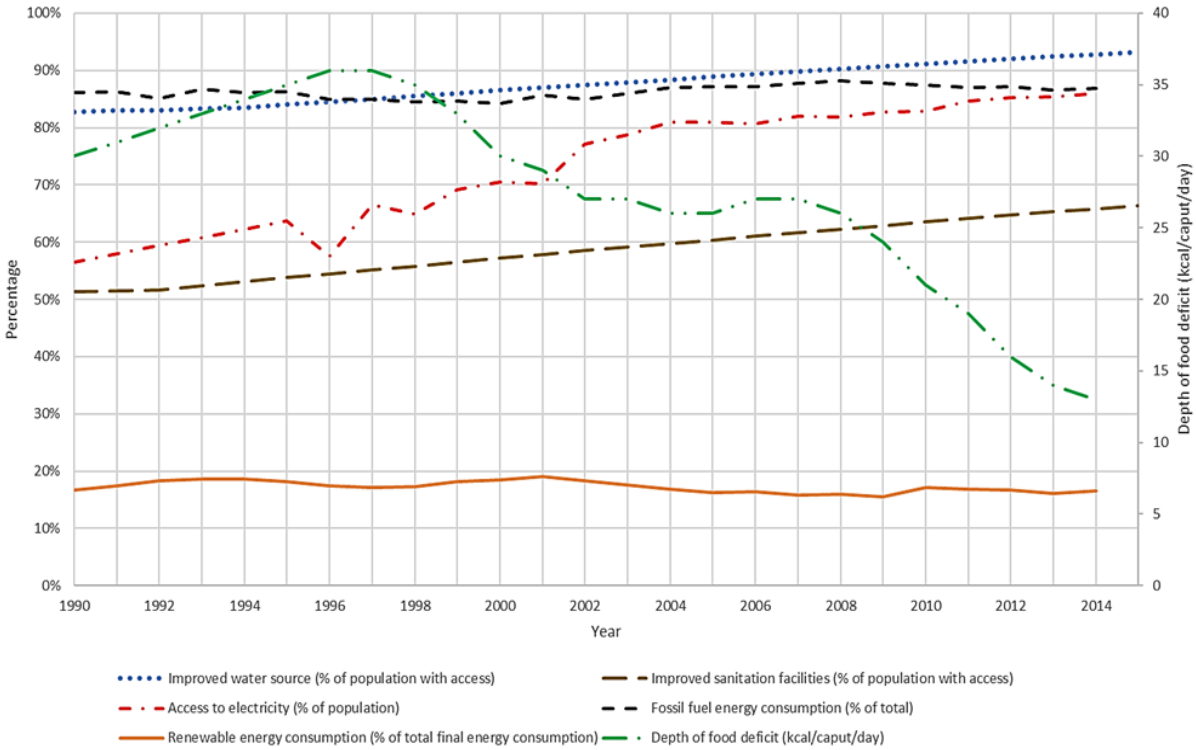

Figure 2.2 Annual change in WEF nexus indicators (improved water source, access to electricity, renewable energy consumption, improved sanitation facilities, fossil fuel energy consumption, and depth of food deficit) from 1990 to 2014 relating to SDGs 2, 6 and 7 overtime in South Africa (FAO, 2017, The World Bank, 2018).

2.5.2 Provincially

Gauteng is the smallest province in South African but is home to more than a fifth of the nation's population. Due to its remote location relative to significant water sources, Gauteng imports approximately 88% of its water via various inter-basin transfer schemes. The province contributes approximately 3% to the total agricultural production but consumes about 20% of these products. The electricity usage of Gauteng is high since it is the economic capital of South Africa, accounting for 24% of South Africa's total electricity delivered in March 2018 (Stats SA, 2019). This provinces' electricity is supplied predominantly by coal-fired power stations in Mpumalanga (Von Bormann and Gulati, 2014a).

The Western Cape Province is responsible for approximately 25% of the agricultural sector's gross income, and exports more than 50% of its produce, 75% of which is destined for the UK and European markets. The provincial government has invested significantly to ensure adequate water quality within this region, as the potential loss of income for produce exports could account for anything between R190 million and R570 million annually (Von Bormann and Gulati, 2014a). In light of the drought that the Western Cape, and in particular Cape Town, has experienced in 2017/8, the sustainability of exporting 'virtual water' in agricultural products will need to be evaluated.

The Northern Cape experiences extreme arid climatic conditions, which is why only 2% of the province is utilised for crop farming. Stock farming accounts for 96% of the province's land utilisation and includes beef, sheep and goats farming. The primary income generator in the Northern Cape is, however, mining. A significant threat to the sustainable development of the Northern Cape is the spread of invasive alien plants, some using as much as 200 million m^3 water annually, which is then unavailable for farmers or rural communities (Hoffman and Ashwell, 2018). Agricultural land is further reduced by the colonisation of alien invasive plants, impacting food production potential. The total reduction in water flows in South Africa, as a result of invasive alien plants, is estimated to be 1 444 million m^3/year, or 2.9% of the naturalised mean annual runoff (C Le Maitre et al., 2016). If these invasive alien species were removed, this water could be used beneficially for food production and domestic or industrial supply. Further, the removal of invasive alien species could function as a feedstock for energy generation from biomass, utilising, for example, the pyrolysis process.

In the Karoo, no large-scale electricity generation projects exist, and the region relies on small solar farms or access to the national power gird. In terms of energy generation, this region has been at the centre of much debate, specifically regarding unconventional energy sources such as shale gas or coalbed methane. To support drilling and hydraulic fracturing, water will be required. This is a very scarce resource in the arid, semi-desert Karoo, and there is a concern regarding the impact of these methodologies on both the quality and quantity of groundwater. Water resource systems and the supporting infrastructure within the Karoo are extremely strained. Only 14% (16 million m^3) of the storage capacity of the Welbedacht Dam is currently available due to unmitigated siltation (Ololade et al., 2017). Smaller towns in the Karoo generally depend on groundwater supply, which emphasises the potential threat that unconventional oil and gas (UOG) operations pose (Ololade et al., 2017).

2.6 Policy Issues and the WEF Nexus

2.6.1 Water Sector

Water is one of the vital strategic sectors of the country, and several other sectors are dependent on the water sector to carry out their activities (e.g. energy and agriculture) (Mabhaudhi et al., unpublished). South Africa faces a mounting challenge to secure a supply of clean water and to protect water resources (Madhlopa et al., 2014). The national government has developed a set of progressive policies and water sector-specific laws that should be properly aligned with the constitution for synergy (Madhlopa et al., 2014).

Based on the studies by Madhlopa et al. (2014) and Mabhaudhi et al. (unpublished), the following legislation, policies, strategies and plans relevant to the water sector have been identified, and are listed in Table 2.2.

Table 2.2: Legislation, policy and strategies for the water sector in South Africa (Madhlopa et al. (2014); (Mabhaudhi et al., unpublished).

Document Name	**Document Type**
Constitution of South Africa (RSA, 1996)	Legislation
National Water Act 36 of 1998 (RSA, 1998a)	Legislation
National Environmental Management Act 107 of 1998 (RSA, 1998b)	Legislation
National Water Resource Strategy 2 (2012)	Strategy
White Paper on a National Water Policy for South Africa (DWAF, 1997)	Policy
National Climate Change Response Policy	Policy
National Development Plan	Plan
Water for Growth and Development (DWA, 2009)	Plan

2.6.2 Energy Sector

In South Africa, the energy sector is regulated by the Department of Energy, which has the constitutional mandate to administer legislation related to the energy sectors (Mabhaudhi et al., unpublished). For the purpose of this report, the policies, acts and strategies that have been identified for the energy sector according to Madhlopa et al. (2014) and Mabhaudhi et al. (unpublished) are listed in Table 2.3.

Table 2.3 Legislation, policy and strategies for the energy sector in South Africa (Madhlopa et al. (2014); (Mabhaudhi et al., unpublished).

Document Name	**Document Type**
National Energy Act 34 of 2008	Legislation
National Energy Regulation Act 40 of 2004	Legislation
National Environmental Management Act 107 of 1998	Legislation
Energy Efficiency Strategy	Strategy
White Paper on the Energy Policy of South Africa (1998)	Policy
White Paper on Renewable Energy (2003)	Policy
National Climate Change Response Policy	Policy
Integrated Resource Plan (2016)	Plan
Integrated Energy Plan	Plan
National Development Plan	Plan
Department of Energy Strategic Plan 2011/12-2015/16	Plan

2.6.3 Food sector

The eradication of hunger and poverty remains central to post-apartheid South Africa's policies (Mabhaudhi et al., unpublished). Similar to water, the right to sufficient food is also enshrined in the Constitution of South Africa (Section 27 (1)(b); (RSA, 1996). This also remains one of the key SDGs within the ambit of the WEF nexus. Within this sector, agricultural plays a critical role in providing food, fibre and income to the rural poor (Mabhaudhi et al., unpublished).

In South Africa, the agriculture sector's is regulated by the Department of Agriculture, Forestry and Fisheries (DAFF), with the Forestry and Fisheries departments previously being under other national departments (Mabhaudhi et al., unpublished). Table 2.4 lists key policies, acts and strategies within the agriculture sector in terms of their alignment to the water-energy-food nexus.

Table 2.4 Legislation, policy and strategies for the food sector in South Africa (Mabhaudhi et al., unpublished).

Document Name	**Document Type**
Livelihoods Development Support Programme	Strategy
White Paper on Agriculture 1995	Policy
National climate change response policy	Policy
Integrated growth and development plan (IGDP) for agriculture, forestry and fisheries	Plan
Conservation of Agricultural Resources Act 1983	Legislation
Draft Preservation and Development of Agricultural Land Bill 2016	Legislation

2.7 WEF Nexus and the Sustainable Development Goals

The Sustainable Development Goals (SDGs) agenda builds on the achievements of the Millennium Development Goals (MDGs) and addresses areas that the MDGs did not achieve. The 2030 Agenda for Sustainable Development was adopted by the United Nations' Heads of State and Government preparing the world towards a sustainable development path (Nhemachena et al., 2018). The seventeen SDGs target addressing social, economic and environmental problems facing countries by 2030 (FAO, 2016). Specifically, the challenges that triggered the development of the SDGs agenda include an increasing world population, climate change, environmental degradation and critical water shortages for domestic and agricultural purposes (Anderson et al., 2016). The SDGs are more focused on human livelihoods, with a total of 169 targets which are global in nature and universally applicable. Additionally, the targets recognise different national realities, capacities and levels of development and valuing national polices. The SDGs agenda introduced an additional complex layer that recognises the linkages between the water, energy and food sectors. The WEF nexus approach suggests that the three sectors are not only interdependent, but they also have impacts on each other (WWF, 2017). With regards to the WEF nexus, the most relevant SDGs are illustrated in Figure 2.3, and include: SDG 2 (zero hunger), SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy).

Figure 2.3 The 17 Sustainable Development Goals agreed upon by 193 countries in 2015 (UNDP, 2015).

Literature has revealed that the evaluation of the SDGs in relation to food, energy and water can be regarded as an important tool to establish a holistic approach towards achieving sustainability and meeting the SDG targets (Yillia, 2016, Biggs et al., 2015, Gupta, 2017). Furthermore, the achievement of the SDGs requires decisions for nexus-based adaptations that take into consideration the need to build climate resilience in economic, social and environmental systems. A study by Simpson and Berchner (2017) proposed the calculation of a WEF nexus index using sustainability level indicators and population vulnerability in terms of that resource in the WEF nexus. Furthermore, human vulnerability indicators are key targets of the SDGs. It is also important to note that considering the SDGs through the WEF nexus lens makes it easier to understand the implications for other goals and accomplish targets across multiple goals (WWF, 2017). Since the implementation of SDGs is both directly and indirectly affected by socio-economic, environmental and political factors, the use of the WEF nexus as a framework to uncover these interconnections will increase the probability of the achievement of SDGs by 2030.

2.8 WEF Nexus Research Gaps

The main outcomes of the discussion are listed below:

- The current approach seems to be silent on wastewater reuse, recycling and sanitation. This needs to be addressed as sanitation is central to discussions on water in South Africa.
- Together with the above, the circular economy needs to be added into the WEF nexus framework or Theory of Change. WEF nexus thinking facilitates the circular economy, and this should be shown clearly.
- Issues related to policies and governance need to be of greater prominence and linked to the outcomes.
- Issues related to data collection and making it available are crucial going forward, and thus should be given attention as everything hinges upon data (quantity, quality and access).
- Temporal and spatial scale should also be given attention to determine whether this should be geo-political or linked to water authorities.
- The whole discussion on the WEF nexus needs to be broadened to include the participation of other sectors. Currently, it is still very water-centric as it is being driven by water experts.

Some of the issues raised above will be considered by the project going into the future.

2.9 Concluding Remarks

The following conclusions are arrived at from the initial research project activities. It is important to note that the findings of this study are not exhaustive; it is quite possible that different and more appropriate approaches may be taken, over and above what is concluded here. As such, the literature review will be treated as a living document for the duration of the project.

3 CHAPTER 3: GENERAL RESEARCH METHODOLOGY

3.1 General

The development and execution of the WEF nexus address cross-cutting issues related to the three sectors and avert non-coordinated decision-making (Fabiani et al., 2020). The WEF nexus helps the sectors not drift from sector-specific targets. WEF are vital resources to preserve local development as they are essential for human survival (Huang et al., 2020). The WEF nexus is an overly complex and progressive system with sceptical characteristics (Van Gevelt, 2020). The analysis is assessed predominantly between two of the three sectors. In the water-food relationship assessment, water demand, irrigation method and efficiency are the main focus (Hua et al., 2020). Sometimes the focus remains sector-based (Wolde et al., 2020). This act of individuals in the research field plays a discourse in the WEF nexus research because the assessment of the sectors must be assessed as a whole, with the sectors' individuality considered. Pairwise assessments have significant limitations as there exist complex trade-offs and synergies in the nexus

In response to future uncertainty on water, energy and food the WEF nexus has gained attention in the research and development communities. The nexus encompasses a broad range of transboundary issues. Studies on this topic vary considerably in terms of their focuses depicting various levels and scales to understand interdependencies and develop management options. Several studies pertaining to calculations of flows and uncertainty among the different domains, assessments of infrastructure, technology and policy applications, and quantifications of system performance have been conducted. As a polycentric approach, the WEF nexus is applied either as an analytical tool, a conceptual framework, and a discourse or as part of a decision support system (DSS).

As an analytical tool, the nexus systematically uses quantitative and qualitative methods to understand the interactions among WEF resources and other resources that are indirectly affected by use of the WEF resources (Nhamo et al., 2019a;). Due to the flexibility of the nexus concept, its application in empirical studies has best served to expand, rather than direct, study scope. Insights tend to be high-level. As a conceptual framework, it leverages an understanding of WEF linkages to promote coherence in policy-making and resource management and enhances sustainability to promote cross-sectoral approaches (Nhamo et al., 2019a). As a discourse, it is a tool for problem framing and promoting cross-sectoral collaboration and as a DSS it is used to inform resource planning and management decisions (Nhamo et al., 2019a).

Many of the studies on the WEF nexus speak to analysis of interdependencies across domains and can be distinguished as one-way impact analysis and interactive impact analysis. Many studies applying the WEF nexus approach fall into the one-way impact analysis, for instance Fiasconaro et al. (2012), Dalla Marta et al. (2014) and Ghani et al. (2019) for sustainable bioethanol production and Hack (2015) and, Dombrowsky and Hensengerth (2018) for sustainable hydroelectric power generation. On the other hand, there is increasing recognition for the application of WEF as a conceptual framework and discourse, hence numerous studies have attempted to present the interactive impacts between different domains by depicting their feedback loops through interactions. As such, changes in the feedback strength and rearrangement of couplings may characterise the dynamics of the system.

3.2 WEF Nexus Frameworks

It is an inventive unified approach that makes it possible for indicators in cross-sectoral sustainability to be devised, to make decisions through an analytical framework that denotes the state of WEF resources (Nhamo et al., 2019). The integrated governance framework would efficiently internalise the consequence of trade-offs and be adequate, empowered and incentivised to manage these trade-offs in a manner that optimises the tenability of resources within WEF (Larcom and Van Gevelt, 2017).

The WEF nexus analytical model has facilitated the management and evaluation of trade-offs and synergies in the utilisation and planning of resources, which former tools were unable to accomplish (Nhamo et al., 2019). The challenge within the existing literature is the methodology obstacle of quantification and interconnectedness in the WEF nexus framework (Li et al., 2016). This is due to the WEF consisting of various measurement units, water is usually measured in cubic metres, energy in kilowatt per hour and food in diverse ways, i.e. value, obesity, calories, malnourishment (Simpson et al., 2020).

3.3 WEF Nexus Tools and Models

The MuSIASEM (Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism) tool was developed to simulate the WEF nexus by means of depicting the metabolic patterns of WEF in relation to the ecological and socio-economic variables. It was originally developed for an energy economy, but can be altered to evaluate the WEF nexus by including water and food in its accounting methodology (FAO, 2013). MuSIASEM allows the simultaneous use of demographic, ecological and social variables even if they are defined on different levels and scales. In this way, it allows effective analysis of the nexus between water, energy and food at a national or sub-national level. Furthermore, MuSIASEM provides feasibility, viability, and desirability checks of proposed scenarios. This tool was used to generate an integrated assessment of the contribution and convenience of CSP and woody biomass as alternative sources for electricity production in South Africa (LIPHE4, 2013). In this case study, quantitative data were used from various published research specifically evaluating the consumption of electricity in South Africa, as well as production factors of CSP and woody biomass-based electricity. The maximum short-term potential of CSP and woody biomass were calculated to be 3 000 GWh and 5 900 GWh, respectively, and requirements are found in Table 3.1.

Table 3.1: Requirements of production factors for scenarios concentrated solar power (CSP) and woody biomass-based electricity (LIPHE4, 2013).

Scenario	**Labour (Mhr/y)**	**Water (hm^3/y)**	**Land (ha)**
CSP	2.7	9.1	5 100
Woody biomass	120	NA	9 241 000

The WEF Nexus Tool 2.0 was developed by the QEERI to evaluate the requirements of water, energy, land, financial budget and carbon production for food supply in Qatar (Wicaksono et al., 2017). The WEF Nexus Tool 2.0 is a scenario-based tool that was created primarily to quantify the resources required for food supply at national scale. The tool allows the user to create various scenarios by means of defining the inputs of water, energy and food portfolios. It has been applied in Qatar, where scenarios were created and assessed by calculating water-, energy- and land requirements, carbon footprint, financial cost, energy consumed though import, and carbon emission through import (Daher and Mohtar, 2015). Multiple scenarios are then generated, and the most appropriate scenario would depend on scientific- and policy inputs. Assumptions and limitations of this tool include:

- Food products assessed are only agricultural crops and exclude meat, dairy, etc.
- No calculations are incorporated to quantify effects on water and soil quality.
- Relationships between system components are based on empirically-based data.
- The tool assumes linear relationships between systems.
- The future projection of prices, population growth, and resource demand is not included.
- The existing tool does not capture the financial costs associated with the use of different water and energy sources.

The WEF Nexus Tool 2.0 presents an opportunity to evolve and develop with specific emphasis on South Africa. It may be further improved by including prediction analyses of population growth, resource demand increase and financial considerations.

A Sankey diagram has been used as a tool to represent the water and energy nexus by means of showing the distribution and connection of water and energy and quantifying flows in each stage of water and energy supply chains (Hu et al., 2013). The Sankey diagram has been used to visualise the water-energy nexus at a household scale in Australia (Kenway et al., 2013), regional scale in China (Hu et al., 2013) and at a national scale in the USA (USDoE, 2014). More recently, it was used to generate the relationships between water, energy and food for the United Kingdom, at a capital, government and household level, using multiregional input-output (MRIO) databases, as can be seen in Figure 3.1. With regards to its applicability for evaluating the WEF nexus in South Africa, it would provide a graphical representation of the complexity of the interlinkages between water, energy and food.

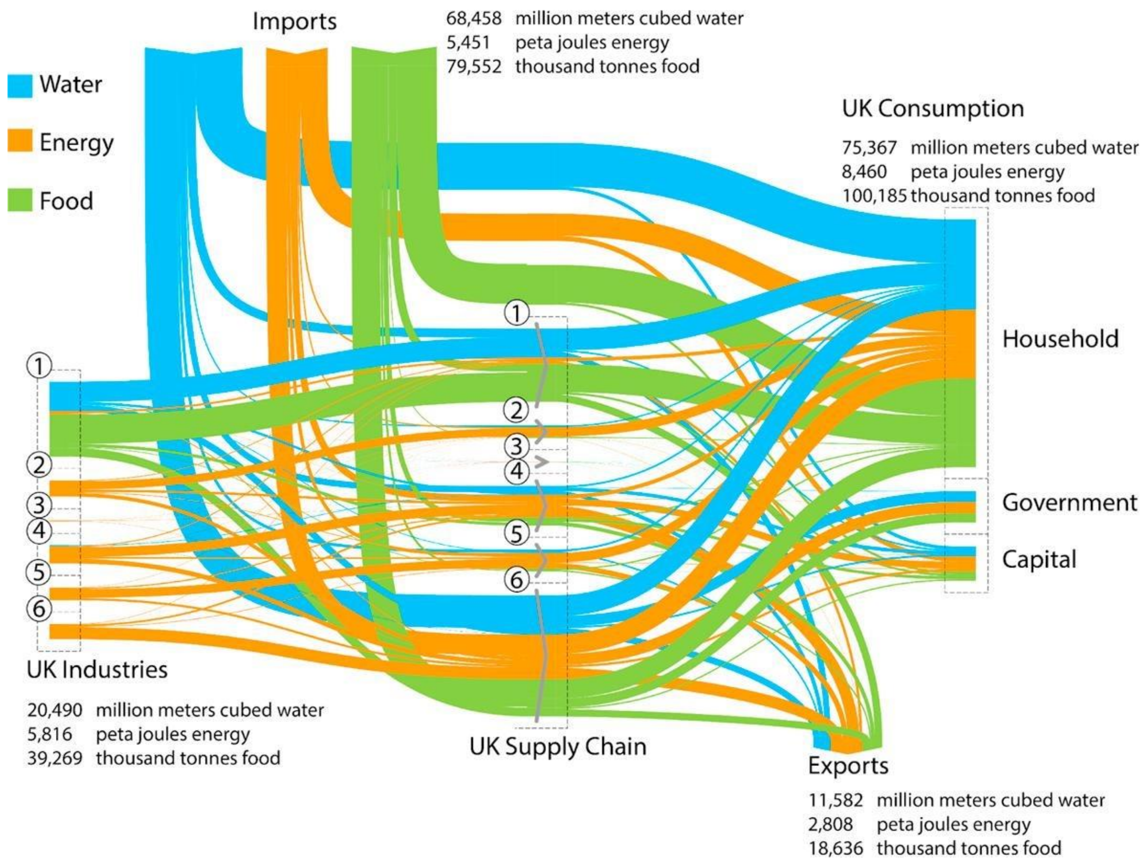

Figure 3.1 Sankey diagram showing water, energy and food flows, from industry to final consumption for the UK in 2013, where 1= agriculture & food processing, 2= power generation and distribution, 3= primary materials industries, 4= manufactured goods & recycling, 5= transport, 6= other services (Owen et al., 2018).

The Foreseer Tool (https://www.foreseer.group.cam.ac.uk) is an online tool that can be used to create Sankey diagrams.

The WEST model demonstrates how the food, energy, and water nexus fits within the broader economy (Reimer et al., 2020). The model also accounts for a production flexibility in which different combinations of inputs can be used to produce a good or service. Business decisions regarding what and how much to produce are based on prices received and the cost of production. The businesses that comprise a sector are often engaged in competition with other businesses. Market economies are common throughout the world and give rise to their own forms of instability (Chaloffet al., 2012).

The WEST model employs numerical optimization methods and is appropriate for market economies in which decisions about water, energy, and food are largely de-centralized. The model is static, starting with an observed nexus outcome and then predicts what happens when an environmental or economic perturbation or “shock” occurs. The model makes predictions about what happens under future scenarios such as declines in groundwater availability and increased demand for food. The model can help researchers capture the conflicting interests faced by community decision makers, such as trade-offs between economic growth and resource conservation. The WEST model can represent systems where there is more than one way to produce a good. For example, a crop could be produced using capital-intensive irrigation equipment that minimizes water use (e.g. drip irrigation), or using inexpensive methods that use less capital (infrastructure) but require more water (e.g. flood irrigation). Similarly, crops can be produced using surface water or groundwater depending on relative scarcity. Production technologies are represented by flexible functional forms that emphasize trade-offs between inputs specific to a given industry. As in standard economic practice, inputs are distinguished into primary inputs (e.g. ground water, surface water, labour, capital) and intermediate inputs, which are outputs produced in the system (such as crops) that are used as an input in other parts of the system (food). The WEST model is based on standard economic analysis as described in Nicholson and Snyder (2012) and Gilbert and Tower (2013).

The model allows for flexible behaviour on the part of economic agents, and so there are many free parameters to estimate. A means of assigning numerical values to model parameters is presented. The process is called calibration and generates information regarding the individual technologies of multiple resource-using economic sectors. The models can also account for whether water rights and water usage can or cannot be transferred across economic sectors. The model is applied to a food and energy producing region that makes intensive use of local resources. Scenario analysis illustrates how the study region could evolve under plausible scenarios involving changes in surface water availability, groundwater availability, and external food demand. The results carry both positive and negative implications for the study area.

The SATIM-W model is a tool that provides insight into the trade-offs when evaluating the linkages between water and energy systems as part of cost-effective sustainable planning (Ahjum et al., 2018). As the name suggests, it is specifically applicable to South Africa, and incorporates large amounts of quantitative data relating to water supply, usage and costs (including water quality and treatment). Furthermore, scenarios include climate change impacts, economic growth, local environmental best practice, policy compliance, and low carbon technologies (Ahjum et al., 2018). To address the hydrological gaps of the model, the World Bank together with the SADC secretariat have launched a regional project to build sustainable groundwater management in the region (The World Bank, 2016). This model may be altered to include the 'food' sector of the WEF nexus as well as social aspects and has great potential to effectively evaluate the WEF nexus in South Africa.

The ANEMI model was established as an integrated assessment model that simulates all relevant variables, such as climate, carbon cycle economy, population, land use, hydrological cycle, water demand and quality (Davies and Simonovic, 2011). Specifically, the ANEMI model focused on revealing the interconnections and feedback of each element. The ANEMI model significantly improves the performance of previous models by including food production and enhancing the potential of optimising the energy-economy element (Akhtar, 2013).

Ozturk (2017) formulated simple non-linear regression equations using a set of explanatory variables of agricultural sustainability, to create understanding of the water-energy-food nexus, within a panel of six sub-Saharan African countries. The study utilised three separate panel regressions, that included the panel least squares regression ('common constant method'); fixed effects ('least squares dummy variables'; and the random effects model ('Dynamic Model').

The Climate Land-use Energy and Water Strategies (CLEWS) modelling framework aims to work with existing models and systems such as Water Evaluation and Planning (WEAP), Long-range Energy Alternatives Planning System (LEAP) and agro-ecological zoning (AEZ) by repeatedly simulating and comparing data between them to find a convergent solution (Keairns et al., 2016). It analyses interlinkages between different resource sectors to determine the effect that one sector might have on the others and identifies counter-intuitive responses in these integrated systems. It is a free online tool that create scenarios based on the following (UN DESA, 2013):

- Global estimates of CO_2 emissions, water use and investment in energy and material production,
- Estimates of CO_2 emissions and water use by energy source, and
- Estimates of mix of energy supply.

This model has been applied to a case study in Mauritius, focusing on two policy goals namely i) renewable energy production, and ii) renewable fuel standard mandating the blending of ethanol into gasoline. Similarly, case studies for Kenya and Bolivia were evaluated, investigating SDG 7 (energy access to all). If this model can be altered, it may be able to explore the WEF nexus in South Africa; however, it seems that it is mainly applied to the energy sector.

When contemplating the future development of WEF Nexus models and indices, Simpson and Berchner (2017a) proposed the development of a composite indicator to report on the WEF nexus. Specifically, their study highlighted that the index should be based upon quantitative data and must be represented by a single numeric indicator, ensuring the evaluation of different cities and countries. Mitigation scenarios could be tested to ensure the establishment of achievable and measurable goals to improve the WEF nexus index over time.

Apart from these tools, models and indices, data storage and accessibility will play a significant role in understanding and analysing the WEF Nexus. Furthermore, it is important to consider temporal and spatial scale differences of the WEF nexus elements, suggesting the need to integrate various available models and tools, as well as the influence of stakeholders and policymakers. Table 5.1, adapted from Martinez-Hernandez et al. (2017b), summarises key models and indices that may be used for nexus evaluation. For this project, models developed by Nhamo et al. (2020) and Simpson et al. (2019) will be used as they facilitate multiscale analyses of resources that are important for advancing food and nutrition security and achieving SDGs 2, 6 and 7. Numerous WEF nexus frameworks have been established. Table 3.2, extracted from Kaddoura and El Khatib, (2017) illustrates the capabilities and limitations of the WEF nexus frameworks. The table details six different frameworks.

Table 3.2 Capabilities and limitations of WEF nexus frameworks

Tool	Capabilities	Limitations
CLEW Framework	Captures Nexus complexity. Good example of systems thinking approach. Considers the climate as part of the nexus.	Extensive data input requirements. Just a framework, not a useable tool. No economic framework. Limited integrated programming within the toolkit.
The Water-Energy-Food Nexus Tool 2.0	Accessible web-based tool. No complex data requirements. Provides a comparable sustainability index. Has an economic module Allows for immediate policy making.	Limited macro-granularity in the results. Static point in time, no future projections. Many missing synergies, e.g. only agriculture is addresses for food. Environmental impacts through carbon emissions only.
MARKAL/TIMES	Good for energy modelling. Captures energy complexities. Time slices available. Allows for evaluating long term sustainability goals. Good example of evolution from an approach perspective.	Not appropriate for short term planning or emergency response. Extensive data inputs. Not a standalone Nexus Tool.
WEAP	Available to developing nations for free. User-friendly UI Includes financial module for project cost-benefit analysis. Adaptable data structure. Flexible time steps for tactical response and long-term planning.	Poor water-energy integration. Accurate models are data intensive. Not a standalone Nexus Tool.
MuSIASEM Flow-Fund Model	Intrinsically considers sustainability of society as funds. Complex Theory normalises quantitative information across different scales for comparison. Can provide snapshot of current metabolic activity.	Does not calculate benefits and costs. Does not study technical variables or outputs versus time. Does not forecast. Must be used in combination with conventional tools. Extensive institutional synergy required to complete the Sudoku effect.
Diagnostic, Financial, and Institutional Tool for Investment in Water for Agriculture	Considers economics and institutional capacity at its core. Identifies investment need and potential. Recommends policy changes. Accessible web-based tool. Economic forecasting Intricate financial tool. Allows for short-, medium-, and long-term investment planning. User-friendly UI. National data for the Indices already available on FAO website.	No technical forecasting. Not a holistic approach, limited to irrigation and hydropower. Financial tool requires extensive technical and economic data.

Source: Kaddoura and El Khatib (2017).

3.4 WEF Nexus Indices and Metrics

The Nexus City Index (NXI), developed by the United Nations, considers food, energy and water resources and includes an equity index. The UN-Habitat approach developed indices to monitor the development of each of the key issues, namely i) productivity index, ii) infrastructure development index, iii) quality of life index, iv) equity index, and v) environmental sustainability index. These five indices are used to form the basis of the NXI, which exhibits the resilience of the urban water-energy-food systems. This approach is based on urban resilience, which is targeted in Goal 11 of the SDGs (Schlör et al., 2018). Along with the NXI_{region}, the World City Prosperity Index, the Regional City Prosperity Index and a Regional City Index (NXI_{city}) were developed to assess the resilience of various regions and cities in the world (Schlör et al., 2018). These indices provide data and serve as decision support for identifying, monitoring, planning and managing the urbanisation process in cities and regions which special attention given to those developments within the WEF sectors (Schlör et al., 2018). These indices are useful in South African terms, but do not consider the impact of policy implications on the outcomes of the indices, nor do they include scenario-based predictions of population growth, climate change or economic growth.

3.4.1 Link to SDG 2 (Zero hunger)

SDG 2 deals with ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture by 2030. It is a comprehensive SDG and an equally important one given that food insecurity and hunger are on the increase in the world, despite all the efforts that are being made. The targets and indicators for SDG 2 are given in Table 3.3 below.

So with regard to the zero hunger SDG 2, the quest is for a set of indicators and metrics that capture the most and is all encompassing. Typically one is looking at food self-sufficiency and cereal productivity (as cereal is the staple of concern) under the pillars of accessibility, availability, affordability and stability. Concomitant with food security is the issue of nutrition security, concerned with intake of adequate nutrients for a healthy and active life. The argument goes that nutrition security encompasses food security, which encompasses nutrient content. Regarding nutrition security, the pillars are similar to food security as in food intake, accessibility, availability and affordability. The indicators of nutrition security tend to be indirect and measured through the most affected members of the population, those under the age of five years, by measuring the proportion of children that are stunted and or wasted or underweight.

Table 3.3 SDG 2 target and indicators (UN, 2016; UNSD, 2016)

Target Number	Target Description	Indicators
2.1	By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.	2.1.1 Prevalence of undernourishment. 2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES).
2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.	2.2.1 Prevalence of stunting (height for age <-2 standard deviation from the median of the World Health Organization (WHO) Child Growth Standards) among children under 5 years of age. 2.2.2 Prevalence of malnutrition (weight for height >+2 or <-2 standard deviation from the median of the WHO Child Growth Standards) among children under 5 years of age, by type (wasting and overweight).
2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.	2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size. 2.3.2 Average income of small-scale food producers, by sex and indigenous status.
2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.	2.4.1 Proportion of agricultural area under productive and sustainable agriculture.
2.5	By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.	2.5.1 Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities. 2.5.2 Proportion of local breeds classified as being at risk, not at risk or at unknown level of risk of extinction.
2.a	Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries.	2.a.1 The agriculture orientation index for government expenditures. 2.a.2 Total official flows (official development assistance plus other official flows) to the agriculture sector.
2.b	Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round.	2.b.1 Agricultural export subsidies.
2.c	Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility.	2.c.1 Indicator of food price anomalies.

3.4.2 Link to SDG 6 (Clean water and sanitation)

With respect to SDG 6 on ensuring availability and sustainable management of water and sanitation for all, the target and respective indicators are summarised Table 3.4 below. More importantly is the understanding and proper interpretation of the indicators for the SDG. The question that arises from the above is, for this research, what is the minimum set of indicators that can be applied as a measure of attaining SDG 6 in South Africa. As indicated in the sections below, for SDG 6, the indicators must capture water availability, accessibility and productivity under the pillars of affordability, stability and safety.

Table 3.4 SDG 6 target and indicators (UN, 2016; UNSD, 2016)

Target Number	**Target Description**	**Indicators**
6.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all.	6.1.1 Proportion of population using safely managed drinking water services.
6.2	By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.	6.2.1 Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water.
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	6.3.1 Proportion of wastewater safely treated. 6.3.2 Proportion of bodies of water with good ambient water quality.
6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.	6.4.1 Change in water-use efficiency over time. 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources.
6.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.	6.5.1 Degree of integrated water resources management implementation (0–100). 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.	6.6.1 Change in the extent of water-related ecosystems over time
6.a	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.	6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan.
6.b	Support and strengthen the participation of local communities in improving water and sanitation management.	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management.

3.4.3 Link to SDG 7 (Affordable and clean energy)

SDG 7 deals with ensuring access to affordable, reliable, sustainable and modern energy for all. It is important to note that the SDG flags sustainable modern energy for all. So the question arises as to whether energy sources such as firewood or coal or peat are sustainable and modern enough to be considered in this goal, or is modern and sustainable only reserved for renewable energies such as solar and wind power. The targets and indicators for SDG 7 are given in Table 3.5 below.

Table 3.5: SDG 7 target and indicators (UN, 2016; UNSD, 2016)

Target Number	Target Description	Indicators
7.1	By 2030, ensure universal access to affordable, reliable and modern energy services.	7.1.1 Proportion of population with access to electricity. 7.1.2 Proportion of population with primary reliance on clean fuels and technology
7.2	By 2030, increase substantially the share of renewable energy in the global energy mix.	7.2.1 Renewable energy share in the total final energy consumption.
7.3	By 2030, double the global rate of improvement in energy efficiency.	7.3.1 Energy intensity measured in terms of primary energy and GDP.
7.a	By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.	7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems.
7.b	By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states and landlocked developing countries, in accordance with their respective programmes of support.	Investments in energy efficiency as a proportion of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services.

As with food and water security, what are the indicators applicable to SDG 7 on energy security? The indicators of concern would include accessibility and productivity of energy under the pillars of reliability, sufficiency, and energy type. The issue of energy type is important, and so is the source of the energy. An interesting example for a country like South Africa is indicator 7.1.1 on 'Proportion of population with access to electricity', although the proportion might be high, the source of the electricity energy (coal fired power stations) is certainly not considered modern, and hence not sustainable in the long run. This is why when one is dealing with these targets and indicators, one take them in their full context and not be selective as that might give the wrong interpretation and conclusion.

3.5 Data Requirements and Scale Issues

Common to all research and applications is the issue of data requirements. This normally presents the so-called ‘data and end product conundrum’ in that one drives the other or the likelihood of one influencing other. In the first case it is argued that the data that is available influences the end product, but then the converse is also true in that the required end product or indicator or metric determines the data that is required thereof. Furthermore, available tools and methodologies determine the data that is required for one to effectively deploy or apply them. Lastly, the researchers’ comfort zone also determines the data that is required, given that researchers have preferences in term of research methodologies, and hence the data that must be generated and applied. Data are a key input in WEF nexus research and application. Of importance are the data quantity, quality and access.

All the above apply to data requirements and data issues with regard to the WEF nexus research, application and operationalising. Because of the complexities associated with the WEF nexus, data requirements can be equally complex or demanding. The following examples will help to drive this point home if one looks at (i) water for food and energy, (ii) energy for water and food and (iii) food for water and energy.

i. *Water for food and energy*: Here one is looking at the following water demands or uses (just to mention a few), and hence the data required and the potential sources of this data in the WEF nexus analysis;
    - Water for irrigation
    - Water for biofuel feedstock production
    - Water for food processing
    - Water for fracting
    - Water for wastewater reclamation
ii. *Energy for water and food*: In this case the demand is for energy and the subsequent data requirements and where to obtain such data; Energy for biofuel feedstock production
    - Energy used for food processing
    - Energy for irrigation
    - Energy losses in transmission
    - Energy demanded in urban areas
iii. *Food for water and energy*: Here one is looking at food demand to meet water and energy operations and activities;
    - Food for biofuels or used as feedstock in bioenergy production
    - Food for energy in irrigation

- Food for water in irrigation
- Environment and health impacts

Other associated complexities include, for example: (i) agriculture and land for energy and water wherein agriculture is an energy user or agriculture as an energy supplier for bioenergy; agriculture and land use and the consequent impact on the water sector; (ii) agriculture, water & the environment where agricultural activities can lead to over-abstraction of water and a decline in ecosystem goods and services.

Also as discussed in the next section, the different research approaches and models/tools used have different data requirements.

With regard to scale issues, the WEF nexus can be operationalised at different spatial and temporal scales, depending on application. In terms of spatial scale (see Figure 3.2) , the WEF nexus can be operationalised from the field scale or household level, scheme (e.g. irrigation) level, district or sub-catchment scale, provincial or catchment scale, national scale, regional or transboundary scale and indeed continental scale. The challenges that one face includes clearly defining system boundaries and quantifying mass and energy flows across boundaries, feed forward and feed backward linkages or loops, and the related data access and its quality. Here in South Africa there are examples of the application of the WEF nexus at the local, catchment and national scale and also regional (SADC) scale.

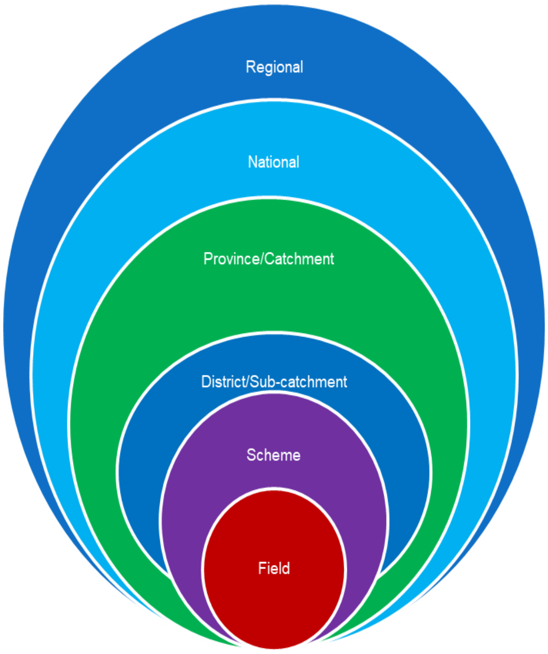

Figure 3.2 Spatial operational scales of the WEF nexus

Looking at spatial scales, the WEF Nexus can be operationalised at any convenient scale, but the most common scales are; past (run WEF nexus scenarios for the past), present or immediate (run WEF nexus case studies for the 'now', i.e. what it is now), intermediate, say to 2030 (run WEF nexus scenarios or analyses into the future, e.g. impact of CC, LU, population dynamics on water, energy and food resource securities), and long term, say beyond 2030 into the distant future (run WEF nexus long term analysis, e.g. CC/CV or LU impacts on the WEF resources). Figure 3.3 below provides an example of an extended time horizon for the WEF nexus. Indeed the WEF Nexus has been run for scenarios into the distant future, like the year 2100.

Figure 3.3 Temporal scale for operationalising the WEF nexus

3.6 Research Approaches

Broadly speaking, there are eight nexus modelling approaches and several authors (Albrecht et al., 2018; Martinez et al., 2018; Zhang et al., 2018) have discussed them in terms of their advantages, disadvantages and applications, and guidance. The appropriate methods vary in response to the scale and research priorities of a specific nexus system. Specifically, a higher degree of data aggregation is likely to be required as the system scale moves up. Methods and approaches in the study of the WEF often use or propose the use of existing disciplinary techniques. According to Albrecht et al. (2018), numerous studies utilize multiple, but often closely related, tools from the areas of environmental management, economics, indicators, statistics and integrated models. Specific tools frequently used include the following:

- *Investigations and Mathematical Statistics* – commonly used to investigate interactions among nexus sectors, and generate data through field surveys, panel experts, public data from government and literature at local and global scales.
- *Computable General Equilibrium Model* – these are applied to economic policy analyses and to evaluate impacts of policies on WEF nexus, e.g. prices and market behaviour. The data requirements include national data on prices, market responses, trade data, and manufacturing data, which is often at a national scale.
- *Econometric Analysis* – used for economic relations and manifests nexus systems through mathematical equations and are set to infer causality and test economic theories. Data requirements include sample sizes and panel data at national and regional scales.
- *Ecological Network Analysis (ENA)* – this is based on input-output analysis and evaluates interactions between economic and natural components, and allows investigation of trade-off between multiple elements. It is mostly done for national and regional type analyses.

- *Life Cycle Analysis (LCA)* – this is widely used for quantifying environmental impacts of products or processes and applied to assess environmental impact of nexus sectors at national, regional and global scales.
- *Systems Dynamic Modelling (SDM)* – this is often a top-down modelling approach, which allows for comprehensive analysis of multi-sectoral systems at micro and macro level. It has been used for developing causal loop diagrams for WEF nexus at local and global scales.
- *Agent-based Modelling* – this is a bottom-up approach but has high data requirements, hence limited applications to date.
- *Integrated Index* – this uses multiple indicators to present various social & environmental characteristics, which allows for analysis of complex nexus systems.

4 CHAPTER 4: DEVELOPING/GENERATING A USEABLE WEF NEXUS FRAMEWORK FOR SOUTH AFRICA

4.1 Introduction to WEF Nexus Frameworks

Water, energy and food security form the basis of a resilient economy (Von Bormann and Gulati, 2014) and sustainable and inclusive development for South Africa (SA). The challenges that SA is facing concerning water, energy and food securities make it imperative that future development be anchored in WEF nexus approaches. The key drivers of these challenges include: (i) increased energy demand to satisfy the country's economic development goals, (ii) rapid population growth, coupled with increased urban migration leading to a need for more food production, (iii) increased physical water scarcity problems into the future being fuelled by climate change, (iv) planned irrigation expansion as a tool for rural development, coupled with the concomitant increased demand for water for agriculture, and (v) the politically explosive poverty-unemployment-inequality nexus bedevilling the country. Therefore, the operationalising the WEF nexus at various spatial and temporal scales within SA has the potential to address the challenges related to water, energy, and food insecurity, and of unemployment and social imbalances (Mabhaudhi et al., 2016a; Nhamo et al., 2018).

The WEF nexus is purposed to promote long-term water, energy, and food security and sustainability, and eventual preparedness to natural shocks through scenario planning (Biggs et al., 2015; Mabhaudhi et al., 2019a). In this regard, the WEF nexus came to the fore as a decision support tool, that (i) indicates the performance of resource utilisation and planning, (ii) establishes a quantitative relationship among interlinked resources, and (iii) indicates priority areas for intervention, aimed at establishing a balanced resource use and planning, and inclusive economic growth for sustainable development (Nhamo et al., 2020). Thus, the method is a catalyst for climate change adaptation and resilience building, by improving human wellbeing and attainment of Sustainable Development Goals (SDGs), particularly SDGs 2, 6, and 7 (Mabhaudhi et al., 2019a; Mpandeli et al., 2018).

Currently, frameworks (institutions, policies and strategies) are developed without adequate consideration for the cross-sectoral consequences, and without considering national targets as part of the SDGs (Mpandeli et al., 2018; Simpson et al., 2019). Lack of synergy between WEF sector role players creates a gap between sectors in terms of demand, supply and implementation. For example, in South Africa, SDGs 2, 6 and 7 are directly linked, and achieving them depends on the sustainable use, access and management of WEF resources (Nhamo et al., 2019a). There is a need for government sectors to move towards policy convergence in order to minimise duplication of activities, create inter-sectoral linkages at technical, policy and political levels. Cross-sectoral impacts and inter-sectoral linkages need to be considered when formulating policies, strategies and plans within the water, energy and agriculture sectors. In addition, these sectors should strive towards communicating such policies, strategies and plans in a transparent manner as well as to cross-reference their decisions. In this regard, understanding the complex relationships of the WEF nexus has become critical to the development of a sustainable and secure future for South Africa (Gulati et al., 2013).

4.2 Criteria for WEF Nexus Development or Selection for South Africa

A review of various existing WEF nexus frameworks to ascertain their applicability to South Africa was done during the project workshop that was held on the 26th April 2018 at the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal, Pietermaritzburg. In total, 20 frameworks were reviewed by the project team. The criteria utilised to evaluate the frameworks included:

- All three sectors: equal weighting (water, energy and food),
- Drivers of change (industrialisation, global change, population growth, urbanisation),
- Challenges facing South Africa (based on the above drivers of change),
- Applicability to South Africa (livelihoods [rural poverty], data requirements, sectoral compartmentalisation [governance/policy], fossil fuels, etc.),
- Integration (does the framework account for integration between the different sectors),
- Other sectors (does the framework acknowledge other sectors such as the environment/ecosystems, land, climate change, livelihoods, waste management, recycling/re-use, etc.),
- SDGs and MDGs (does the framework account and connect to the development goals), and
- Innovations (such as improved infrastructure, e.g. power stations, improved technology, etc.).

4.3 Specific WEF Nexus Frameworks and Suitability to South Africa

Based on these criteria, five existing frameworks were identified to be most applicable in terms of bringing about policy alignment and coherence for South Africa. The five frameworks were are summarized below as follows:

- The study by Smajgl et al. (2016) presented a sectorally balanced, dynamic, WEF nexus framework where sectoral objectives are given equal weightings. Analyses in the study showed that this type of framework reveals the emergences and/or changes in cross-sectoral connections because of single sector interventions. The dynamic WEF nexus framework describes interactions between (a) the three sectors as well as (b) between the nexus core and the three sectors
- Ringler et al. (2013) presented the concept of the water-energy-land and food (WELF) nexus. The study indicates that this concept is known to play out differently in various parts of the world. The WEF nexus framework evaluates the linkages that exist among the water, energy, land and food sectors. The direct and indirect drivers of change, which affect these linkages, are clearly depicted in the framework. In most existing WEF nexus frameworks, the land

dimension in not included, however this framework considers the dimension of land as it recognises its importance not only in the production of food but also for water (underground water storage, reservoirs) and in energy supply (shale gas or biofuels).

- Karabulut et al. (2018) proposed a synthesis matrix system which describes the complex and closely related relationships that exist between the natural resources used for food (specifically water and land), energy (which is defined as ecosystem service flows in the matrix system) and ecosystems, within the WELF concept. The matrix system can be defined for different scales (from global to local) and includes the impacts and nexus with climate change. The aim of the matrix is to integrate quantitative and qualitative aspects, which are often neglected in conventional approaches of impact assessment. Because of the complexity of interactions between the different components of the nexus, quantitative and expert judgement are both required. In this framework, ecosystems represent the most significant component of the nexus as it incorporates all features that support water, energy, land and food availability and production
- Martinez-Hernandez et al. (2017a) presented in this study a simulation and analytics framework, and a concomitant Nexus Simulation System termed "NexSym". The purpose of this study was to develop a framework/tool for integrated resource assessment, accounting for integration within and across WEF sectors, ecosystems and consumption components that interact with a local system. Martinez-Hernandez et al. (2017b) indicated that there is a need for a nexus tool on a local scale as solutions are better tailored to local conditions, and it becomes easier to achieve synergistic techno-ecological interactions.
- Conway et al. (2015) examined southern Africa's nexus from the perspective of climate and a modified Hoff's nexus framework (Hoff, 2011), which integrates global trends (drivers) with fields of action, to highlight the role of climate as a driver. The framework in this study considered the main elements of intra-regional links, which occur in WEF sectors at a national level while highlighting connections on the river basin scale and drawing attention to case studies of the many examples of specific trade-offs and synergies.

Based on the review of the various frameworks, the project team sought to develop/modify the existing frameworks for more applicability and relevance to South Africa:

4.3.1 Innovations

A recommendation to improve the scores for this component within the criteria and to make the framework more relevant and applicable for South Africa would be to account for innovations such as improved infrastructure (e.g. power stations with lower emissions and/or dry-cooled power plants), renewable energy technologies (biofuels, wind, tidal and the use of abundant solar energy), technological advances (for data models and systems to develop as more data is required which will contribute towards a better understanding of the nexus approach and to inform decision making, for ease of disseminating and sharing data), working towards improving the efficient use of water (desalination, establishing dry-cooled power plants) as well as the option of seasonal climate forecasting (climate change adaptation for farmers).

4.3.2 SDGs

With the emergence of the SDGs, the WEF nexus has been recognised as a key tool for regional integration and development, as well as to achieve the national SDGs targets (Mabhaudhi et al., 2016b). It is also anticipated that SDGs will drive future policies since the targets of the SDGs 6, 7, 8 and 9 are related to the water-energy nexus planning approach. The WEF nexus has been identified as an approach to achieving SDGs 2, 6 and 7.

SDG 2 accounts for zero hunger, SDG 6 refers to clean water and sanitation, SDG 7 focuses on affordable and clean energy, SDG 8 comprises of affordable work and economic growth while SDG 9 is aimed at industry, innovation and infrastructure. Hence, it is crucial that the frameworks mention and account for the above SDGs (or the MDGs if the SDGs were not yet in place) as well as illustrate how the SDGs connect with the three primary sectors under consideration. For example, SDG 2 can be achieved by eradicating food insecurity, improving nutrition. SDG 6 can be achieved by ensuring basic access to water and sanitation and tackling the issue of water scarcity. SGD 7 requires the promotion of renewable energy sources, and access to these power sources. SDG 8 focuses on job creation, educating the unskilled workforce, as well as working towards a sustainable economic development, while SDG 9 requires improvements in infrastructure, technology and industrialisation.

4.3.3 Challenges

With specific reference to studies by Karabulut et al. (2018) and Martinez-Hernandez et al. (2017a), these frameworks scored low for challenges and should take into account livelihoods (rural poverty, high rates of unemployment, educating the poor, electricity shortages, land issues), nutrition, health and food insecurity (agricultural sector), improving economic growth, water scarcity within the context of climate change, data requirements and availability (data is often scattered, have different spatial scales, possess limited comparability or do not represent temporal trends, human and financial capacity constraints) as well as the lack of sectoral compartmentalisation (governance and/or policies).

4.3.4 Integration

The framework by Conway et al. (2015) was amongst the top five relevant frameworks for South Africa that had the lowest score for integration, hence in order to modify the framework for applicability to South Africa, the framework should account for integration between the three sectors (water, energy and food) more strongly. Despite mentioning the three sectors, the framework should illustrate how the sectors merge as well as state possible solutions to improve integration.

4.3.5 Acknowledging other sectors

The WEF nexus framework by Conway et al. (2015) while serving its climate change focus, could illustrate or portray the connections and relationships between sectors, feedback and interlinks if it is to be more relevant to South Africa. While a WEF nexus framework cannot be all things to all people, it is to be applicable to South Africa it needs to acknowledge and account for livelihoods, land, ecosystems/environment, climate change, waste recycling and reuse.

These recommendations are proposed in order to improve and modify the existing frameworks for better application to the context in South Africa.

4.4 Proposed and Selected WEF Nexus Framework for South Africa

4.4.1 Mabhaudhi et al (2019) Sustainable Livelihoods WEF Nexus Framework

Figure 4.1 is a schematic of a was initially proposed WEF nexus framework for South Africa. The WEF nexus framework was developed considering the issues relevant to South Africa, thus making the framework applicable to the country. As mentioned previously, a criterion was used to select the top five WEF nexus frameworks in terms of relevance to South Africa.

The top three frameworks by Smajgl et al. (2016), Ringler et al. (2013) and Karabulut et al. (2018) were used in conjunction with the framework by Hoff (2011) to assist in designing the WEF nexus framework for South Africa. Figure 4.1 illustrates the vital drivers of change and/or challenges that South Africa must deal with, strongly influence the WEF nexus. The figure also illustrates that with appropriate policies, strategies, and the consideration of alternative clean, renewable options, a state of human well-being and environmental sustainability can be achieved. The WEF nexus framework had also been designed with SDGs 2, 6 and 7 being considered.

The nexus framework describes the interactions between the three sectors. The direct and indirect drivers of change, which affect these linkages, are also illustrated in the framework (Figure 4.1). The WEF nexus' core consists of the drivers that are critical to the water, energy, food sectors, and the cross-sector feedbacks in South Africa. Due to the aforementioned as well as being vital elements to human well-being, they are placed in the centre of the nexus.

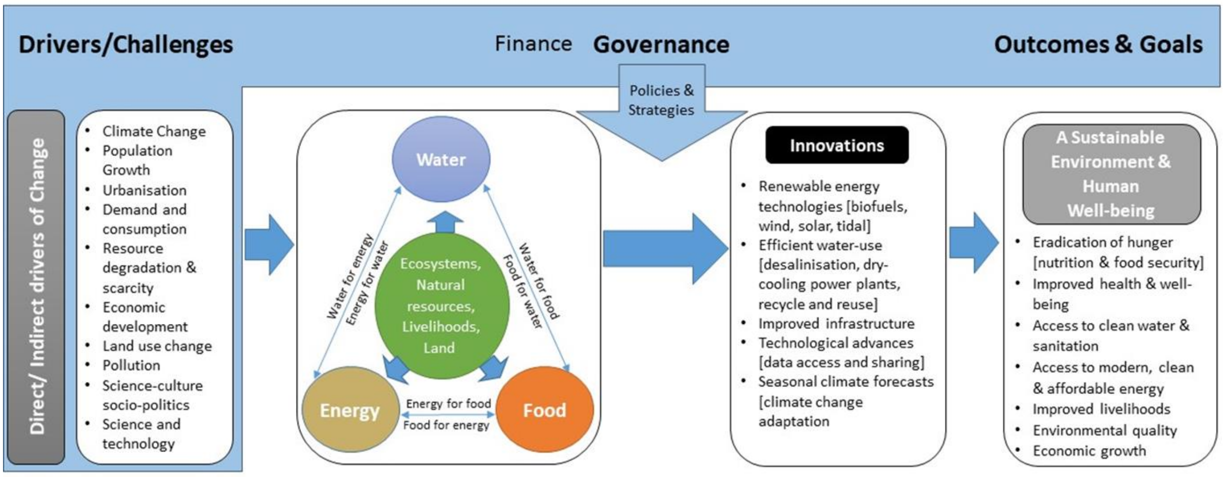

Figure 4.1 A Proposed WEF nexus framework for South Africa with particular emphasis on Sustainable Development Goals (SDGs) 2, 6 and 7 (modified after Smajgl et al. (2016a), Ringler et al. (2013), Karabulut et al. (2018) and Hoff (2011))

4.4.2 Simpson et al (2020) Anthropocentric WEF Nexus Framework

Simpson et al. (2020) presented an anthropocentric WEF nexus framework, as seen in Figure 4.2, which places equity and humanity at its centre, through which the different perspectives and elements within this system are considered and represented (Simpson et al., 2020). This framework is in contrast to many WEF frameworks, which emphasise interactions between the resources sectors but do not accentuate the role of society as both a manipulator and beneficiary of the system. Water, energy, and food are ultimately obtained from the natural resource base (Rockström and Sukhdev 2016) and the flow of resources from the environment to the source of demand, i.e. humans, is, therefore, the dominant driver within this system. Further, the climate and environment are managed and regulated through sound (or poor) governance and policies, as shown by the two intermediate layers within the proposed framework. At the core of this framework are the equitable ‘access’ and ‘demand’ related to the three core resource sectors, i.e. ‘leave no one behind’, and the managing of the global supply chain system.

This proposed framework is said to be especially applicable to developing regions/countries due to its emphasis on SDGs 2, 6 and 7. The goal of this conceptual framework is to guide the development of tools to address Africa’s policies that promote equitable access to resources, sustainable development and the protection of the environment and environmental rights. It was developed specifically to guide the development of the WEF nexus-based composite indicator detailed in this article.

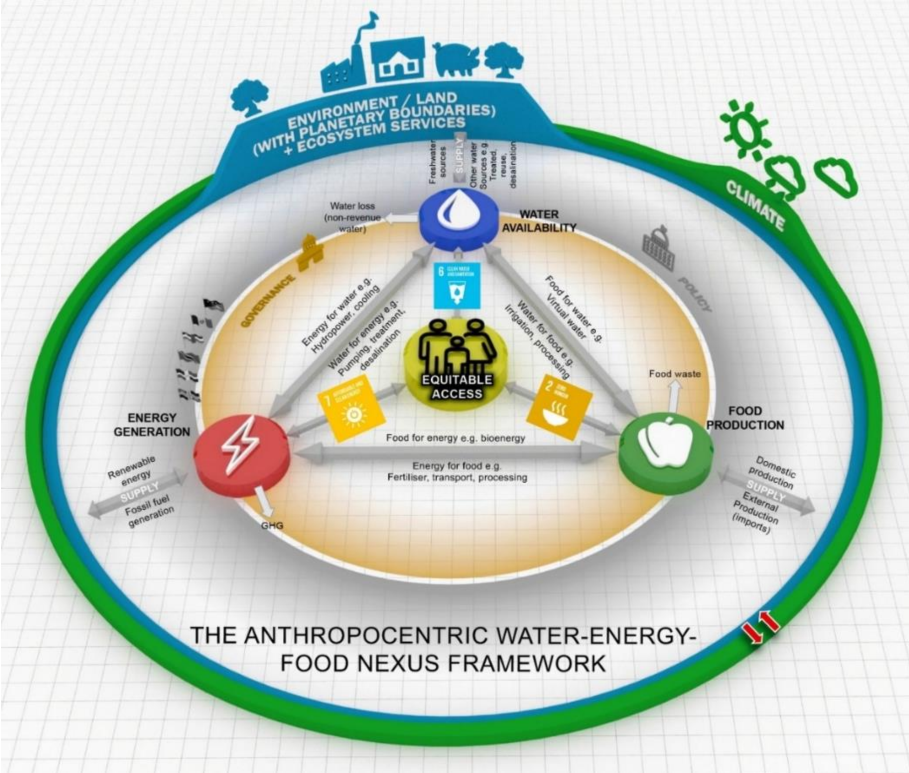

Figure 4.2: The Anthropocentric WEF Nexus Framework (Simpson et al., 2020)

The link between each of these resources and the core of the framework shown in Figure 4.2 is, however, not limited to the supply of water, energy and food. Equitable access, represented by SDGs 2, 6 and 7, form the second component of the link between the respective resources and people. According to Simpson et al. (2020), the interdependencies between the three sectors are represented by the direct links between water availability, energy generation, and food production. The supply of water, energy, and food are ultimately obtained from the natural realm. The climate influences the environment, which is, in turn, influenced by how these resources are 'procured'. This supply can be either renewable or non-renewable. In the case of food, it could be domestic production thereof or imported food. All levels of the system, including the environment and/or land use, are influenced by policies and governance, which are dependent on people. Humanity, therefore, drives the global supply chain system from the centre of this framework, while yielding a dominant influence throughout the framework. If people are to obtain all that they demand from Earth in the long-term, then they must, in turn, govern wisely and develop appropriate, integrated policies. Resource demand management (SDGs 15), sustainable supply (SDG 8.4/12.2/12.5), and the reduction of greenhouse gases and climate resilience (SDG 13.1) and food waste are also imperative and indirectly linked to WEF nexus approaches (Simpson et al., 2020).

4.5 Concluding Remarks

The status quo of the WEF nexus in South Africa is of great value, especially when developing a framework that is specific for the country. The WEF nexus framework that was designed in this project considers the importance of livelihoods and human-wellbeing, an imminent threat to sustainable development, especially within South Africa. Current literature shows that policies, strategies and plans have not fully embraced the applicability of the WEF nexus to sustainable resource management with some documents only referring to its existence. More research is needed involving policymakers, researchers, and stakeholders to provide a comprehensive perspective on the desirability of implementing WEF nexus thoughts in South Africa.

5 CHAPTER 5: SELECTING A WEF NEXUS MODEL FOR SOUTH AFRICA TO STUDY TRADE-OFFS IN THE USE OF WATER AND FOOD FOR FOOD AND NUTRITION SECURITY

5.1 Introduction to WEF Nexus Tools and Models

To accurately model and assess the WEF Nexus, it is useful to generate data that will be able to quantify flows of energy and materials, make numerical predictions and estimate the associated costs (Keairns et al., 2016). Recent work of Ravar et al. (2020) presented a spatiotemporal disaggregate water-energy-food nexus model to assess water and food supply security at a river basin scale in Iran. At the Urmia lake Basin in Iran, Bakhshianlamouki et al. (2020) developed a System Dynamics Model (SDM) to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin. In a previous work, Laspidou et al. (2018) defined the elements of a five-component nexus system (water, energy, food, land, climate). They described their complex interactions, while in Laspidou et al. (2019), the authors proposed a heuristic algorithm for assessing sector vulnerability and strength of influence of each nexus sector on others. This assessment was done based on expert opinion and after recording stakeholder concerns. More recently, Laspidou et al. (2020) presented a comprehensive SDM that establishes and quantifies interlinkages among resources and Nexus components by mapping data and incorporating outputs from well-established models. The establishment and quantification of interlinkages by Laspidou et al. (2020) thus allowed for a modelling platform that can incorporate various data sets and modelling outputs in order to run scenarios and produce forecasted trends for future decades. When developing or considering models to guide data generation, it is important to restrict the modelling scope to parts of the WEF nexus to eliminate complexity, but to be aware that there are risks associated with the possible omission of essential interactions and to develop assumptions associated with these risks. To incorporate the necessary aspects of WEF nexus modelling, the involvement of stakeholders in the assessment process is also stressed, which may represent a trade-off between indicator-based assessments and elaborate numerical approaches (Keairns et al., 2016). The following section will discuss the indices, metrics and models that could be used to evaluate the WEF nexus.

Currently, the most commonly used quantitative tools for researching the WEF nexus include material flow analysis (MFA) (Islam et al., 2021; Ngammuangtueng et al., 2019; Terrapon-Pfaff et al., 2018), life-cycle assessment (LCA) (Del Borghi et al., 2018; Gu et al., 2018; Litskas et al., 2019; Mannan et al., 2018; Pacetti et al., 2015; Risch et al., 2014), and input-output analysis (IOA) (Elagib et al., 2019; White et al., 2018). Material flow analysis MFA can help describe the movement path of resources; LCA can help identify hidden environmental impacts, and IOA can deepen understanding of the connection between resource inputs and the resulting outputs.

5.2 Specific WEF Nexus Models and Suitability to South Africa

The SATIM-W model is a tool that provides insight into the trade-offs when evaluating the linkages between water and energy systems as part of cost-effective sustainable planning (Ahjum et al., 2018). As the name suggests, it is specifically applicable to South Africa, and incorporates large amounts of quantitative data relating to water supply, usage and costs (including water quality and treatment). Furthermore, scenarios include climate change impacts, economic growth, local environmental best practice, policy compliance, and low carbon technologies (Ahjum et al., 2018). To address the hydrological gaps of the model, the World Bank together with the SADC secretariat have launched a regional project to build sustainable groundwater management in the region (The World Bank, 2016). This model may be altered to include the 'food' sector of the WEF nexus as well as social aspects and has great potential to effectively evaluate the WEF nexus in South Africa.

The ANEMI model was established as an integrated assessment model that simulates all relevant variables, such as climate, carbon cycle economy, population, land use, hydrological cycle, water demand and quality (Davies and Simonovic, 2011). Specifically, the ANEMI model focused on revealing the interconnections and feedback of each element. The ANEMI model significantly improves the performance of previous models by including food production and enhancing the potential of optimising the energy-economy element (Akhtar, 2013).

Ozturk (2017) formulated simple non-linear regression equations using a set of explanatory variables of agricultural sustainability, to create understanding of the water-energy-food nexus, within a panel of six sub-Saharan African countries. The study utilised three separate panel regressions, that included the panel least squares regression ('common constant method'); fixed effects ('least squares dummy variables'; and the random effects model ('Dynamic Model').

The Climate Land-use Energy and Water Strategies (CLEWS) modelling framework aims to work with existing models and systems such as Water Evaluation and Planning (WEAP), Long-range Energy Alternatives Planning System (LEAP) and agro-ecological zoning (AEZ) by repeatedly simulating and comparing data between them to find a convergent solution (Keairns et al., 2016). It analyses interlinkages between different resource sectors to determine the effect that one sector might have on the others and identifies counter-intuitive responses in these integrated systems. It is a free online tool that create scenarios based on the following (UN DESA, 2013):

- Global estimates of CO_2 emissions, water use and investment in energy and material production,
- Estimates of CO_2 emissions and water use by energy source, and
- Estimates of mix of energy supply.

This model has been applied to a case study in Mauritius, focusing on two policy goals namely i) renewable energy production, and ii) renewable fuel standard mandating the blending of ethanol into gasoline. Similarly, case studies for Kenya and Bolivia were evaluated, investigating SDG 7 (energy access to all). If this model can be altered, it may be able to explore the WEF nexus in South Africa; however, it seems that it is mainly applied to the energy sector.

When contemplating the future development of WEF Nexus models and indices, Simpson and Berchner (2017a) proposed the development of a composite indicator to report on the WEF nexus. Specifically, their study highlighted that the index should be based upon quantitative data and must be represented by a single numeric indicator, ensuring the evaluation of different cities and countries. Mitigation scenarios could be tested to ensure the establishment of achievable and measurable goals to improve the WEF nexus index over time.

Apart from these tools, models and indices, data storage and accessibility will play a significant role in understanding and analysing the WEF Nexus. Furthermore, it is important to consider temporal and spatial scale differences of the WEF nexus elements, suggesting the need to integrate various available models and tools, as well as the influence of stakeholders and policymakers. Table 5.1, adapted from Martinez-Hernandez et al. (2017b), summarises key models and indices that may be used for nexus evaluation. For this project, models developed by Nhamo et al. (2020) and Simpson et al. (2019) will be used as they facilitate multiscale analyses of resources that are important for advancing food and nutrition security and achieving SDGs 2, 6 and 7.

Table 5.1: Potential models and indices that could be used to evaluate the water-energy-food nexus in South Africa (adapted from Mabhaudhi et al., 2018).

Tool	**Modelling framework**	**Scale**	**System breadth**	**Analytical capability**	**Flexibility**	**Applicability to WEF nexus in South Africa**
GLOBIOM	Dynamic multiregional partial equilibrium model	Global	WEF nexus and other interacting systems such as ecosystems	Geographically-explicit and long-term management of global land uses	Focused on land uses	No; only applicable at a global scale
WEF Nexus Tool 2.0	Input-output	National	WEF nexus components	Scenario-based for given food self-sufficiency level calculates nexus resource flows and interactions, and greenhouse gas (GHG) emissions	Focused on food as entry point and Qatar country	Yes
MuSIASEM	Input-output, nested hierarchical view of the economy	Aggregated to national or sub-national level	WEF nexus components, land, economy, human capital and ecosystems	Accounting of flows and funds and their ratios as indicators. GHG emissions and land-use	Adaptable to various contexts	Yes; it has already been applied to South Africa
CLEWS	Integrates detailed models from different tools (including WEAP, LEAP and AEZ)	National	Climate, Land, Energy and Water	Depend on the tools used for the CLEW assessment	Depend on the tools used for the CLEW assessment	Yes; if the model can be changed to evaluate the intersectoral influences of the WEF nexus components
Quantitative assessment framework	Input-output based on Lontief matrices	National	WEF nexus components	Scenario-based, accounting of nexus resource consumption and interdependency indicators	Fixed defined technologies and interactions	Yes; could be extended to analyse the influence of socio-economic factors
DEA	Data Envelopment Analysis Model	Local (city level)	WEF nexus components	Input-output efficiency		No; cannot be used for national evaluation of the WEF nexus
PRIMA	Integrates regional climate, hydrology, agriculture and land use, socioeconomics and energy systems sector models	Regional	WEF components, economy, land use	Climate change related analyses and costs, land use, greenhouse gas emissions	Flexible, portable and modular	No; only relevant for regional decision-making

Tool	Modelling framework	Scale	System breadth	Analytical capability	Flexibility	Applicability to WEF nexus in South Africa
ANEMI	Integrated assessment model	All scales	Climate, carbon cycle economy, population, land use, hydrological cycle, water demand and quality	Reveals the interconnections and feedback of each element	System dynamic simulation	Yes
Sankey diagram	Graphically represents the complex conversion pathways, flows and interdependencies between variables	All scales	WEF nexus components	Based on the data input	Adaptable to various contexts	Yes
Nexus City Index	Measures the prosperity and sustainability of the FEW nexus for 69 cities	All scales	WEF nexus component, prosperity	A top down urban WEF nexus approach which aggregates the WEF sectors to a single indicator	Flexible, and includes likewise indices World City Prosperity Index, the Regional City Prosperity Index and a regional city index	Yes
MESSAGE	Modelling potential future energy scenarios	Global and Regional	Energy and greenhouse gas emissions	Dynamic linear programming model and can be linked with MAGICC (a separate program for predicting GHG-induced climate change) and GLOBIOM		No; does not consider all WEF nexus components.
Integrative WEF Nexus Analytical Tool*	Input – output, nested with Analytic Hierarchy Process (AHP)	Global, Regional, local	WEF nexus components	Based on the data input		Yes; if the model can be changed to evaluate the intersectoral influences of the WEF nexus components
WEF Nexus Index Global Model**	Input-output	Global, Regional, local	WEF nexus components, Socio-economic and bio-physical components	Based on the data input	Adaptable to various contexts	Yes; if the model can be changed to evaluate the intersectoral influences of the WEF nexus components

*Nhamo et al. (2020); **Simpson et al. (2019).

5.3 Selected WEF Nexus Model for South Africa

Given the above suite of potential WEF nexus models and tools, in this project two WEF nexus models, developed in South Africa and paying attention to South Africa's needs, were selected. As indicated in Table 5.1 above these models were Integrative WEF Nexus Analytical Tool (iWEF) and WEF Nexus Index Global Model. Both models' developments were funded by the Water Research Commission of South Africa. The WEF Nexus Index Global Model will not be discussed any further as it operates at the national or country level. Brief details of the iWEF model are given in the following sections.

5.3.1 Integrative Analytical WEF Nexus Model (Nhamo et al., 2020)

The Integrative Analytical WEF Nexus Model was originally developed by Nhamo et al. (2020a) as an MS Excel-based model for establishing 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. To facilitate WEF nexus performance assessment, monitoring and evaluation, the Integrative Analytical WEF Nexus Model holistically evaluates synergies and trade-offs to improve efficiency and productivity in resource use and management for sustainable development.

After identifying and defining relevant WEF sustainability indicators, Nhamo et al. (2020a) developed a methodology to compute composite indices. The key input data for Integrative Analytical WEF Nexus Model are the six WEF sustainability indicators, per annum, including water availability (m^3/capita), water productivity ($/$m^3$), energy accessibility (%), energy productivity (GDP/MJ), food self-sufficiency (%) and cereal productivity (kg/ha). These indicators are compared pairwise in a pairwise comparison matrix (PCM) based on expert opinion/advice, 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., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b). Water availability is the proportion of available freshwater resources per capita, which estimates the total available freshwater water resources per person. Water productivity is the proportion of crops produced per unit of water used, which measures the output from an agricultural system in relation to the water it consumes. Energy accessibility is the proportion of the population with access to electricity, expressed as a percentage (%) of the total population. Energy productivity is synonymous with energy intensity, which is the energy supplied to the economy per unit value of economic output. Food self-sufficiency is the percentage (%) of individuals in the population, out of total population, who have experienced food insecurity at moderate or severe levels during the reference year. Cereal productivity is considered the proportion of sustainable agricultural production per unit area (Nhamo et al., 2020a).

Computations in the Integrative Analytical WEF Nexus Model

The Integrative Analytical WEF Nexus Model integrated the six WEF indicators through the Analytic Hierarchy Process (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 theory of measurement for deriving ratio scales from both 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 nine as indicated in the Table 5.2 (Saaty, 1987).

Table 5.2 Saaty's scale of relative importance for pairwise comparisons in an AHP

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Element *a* and *b* contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour element *a* over *b*
5	Essential or strong importance	Experience and judgment strongly favour element *a* over *b*
7	Very strong or demonstrated importance	Element *a* is favoured very strongly over *b*; its dominance is demonstrated in practice
9	Extreme or absolute importance	The evidence favouring element *a* over *b* is of the highest possible order of affirmation
2 (weak), 4 (moderate plus), 6 (strong plus), 8 (very, very strong), 1/2, 1/4, 1/6, 1/8	Intermediate values between the two adjacent judgments	When compromise is needed. For example, 2 can be used for the intermediate value between 1 and 3
1/3	Moderately less important	
1/5	Strongly less important	
1/7	Very strongly less important	
1/9	Extremely less important	
Reciprocals of above nonzero	If *a* has one of the above nonzero numbers assigned to it when compared with *b*, then *b* has the reciprocal value when compared with *a*	A reasonable assumption

Source: Saaty and Vargas (2012)

Based on the AHP method, the first computation step in the Integrative Analytical WEF Nexus Model calculates the consistency ratio (CR) which measures the randomness and consistency of the pairwise judgements in the PCM, based on equations outlined in Mu and Pereyra-Rojas (2017). Using the PCM, the model would then proceed to calculate the normalised indices for each indicator, and the integrated WEF nexus index which measures the nexus performance of the WEF system as categorised in Table 5.3. The governing equations are presented in detail in the founding publications for the

Integrative Analytical WEF Nexus Model (Mabhaudhi et al., 2019; Nhamo et al., 2019; Nhamo et al., 2020a; Nhamo et al., 2020b).

Table 5.3 WEF nexus indices performance classification categories

Index	Category and Interpretation			
	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)

5.3.2 Upgraded iWEF Model (Nhamo et al., 2022)

Key features of the upgraded iWEF model

The major limitations in the Integrative Analytical WEF Nexus Model developed by Nhamo et al. (2020a) included (i) unavailability in the public domain, (ii) lack of a user-friendly graphical user interface (GUI), and lack of geospatial analytic capabilities. This motivated the development of a user-friendly 'web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical modelling tool' (in short and hereafter, iWEF) building on previous work by Mabhaudhi et al. (2019), Nhamo et al. (2020a) and Nhamo et al. (2020b). Additional key features of the iWEF model, in addition to the operating principles in the original model, included:

- web-basing for open and free access by interested users,
- GIS-enabling for (i) locating case studies, and (ii) spatial analysis, mapping and visualization of the WEF nexus,
- an interactive and user-friendly GUI,
- functions for automatically calculating the consistency ratio (CR), comparing it with established thresholds (less 0.1 as a decimal, or 10% as a percentage) and advising user to revise judgements in PCM accordingly.

The iWEF modelling tool: conceptual model, modules and user operating procedure

The iWEF tool's conceptual model (Figure 5.1) is founded on the AHP multi-criteria decision-making (MCDM) hierarchic framework, which consists of the goal, indicators and pillars. The six indicators are the multiple criteria, and they were elaborated on in Section 2.1 as well as by Mabhaudhi et al. (2019), Nhamo et al. (2020a) and Nhamo et al. (2020b). Nhamo et al. (2020a) and (Nhamo et al., 2020b). Related to the conceptual model is the flow of data for the iWEF model between the four major sub-modules: the database, user interface, computations and results (Figure 5.2).

The modules (Figure 5.2) in iWEF model work harmoniously to enable the iWEF model to fulfil its functional expectations. Generally, the GUI allows users to interact with the iWEF's 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 available online for free access [https://www.iwef.app/, (Taguta et al., 2022a)]. To operate iWEF, users must chronologically follow the steps presented in Figure 5.3. The key outputs in the iWEF model are quantitative, graphical and spatial. The spider diagrams show normalized indices of performance and interrelationships between WEF sectors. The maps show location of case study and spatially visualize the integrated WEF nexus index as a measure of WEF nexus performance.

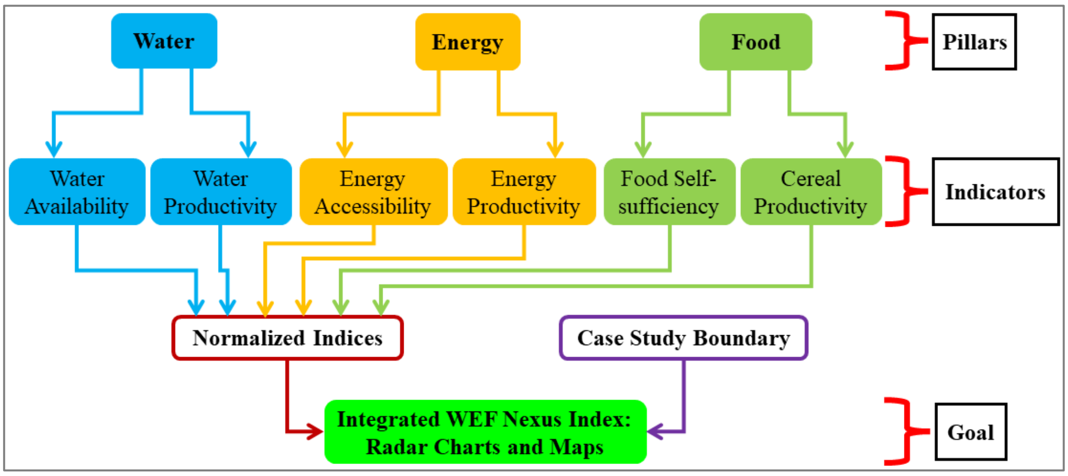

Figure 5.1 The conceptual model for iWEF tool

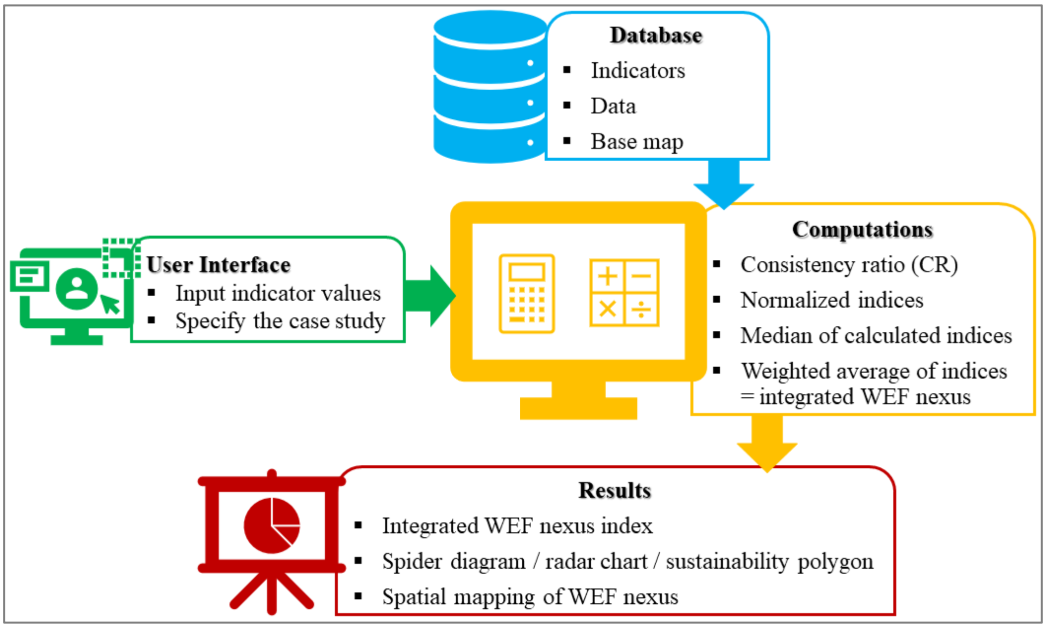

Figure 5.2 The mode of operation for iWEF using the modelling tool's sub-modules

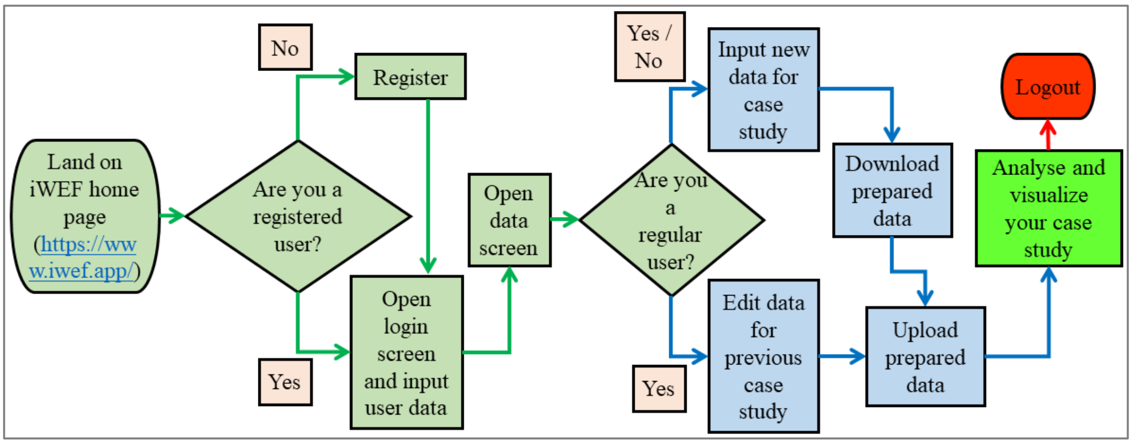

Figure 5.3 The user flowchart for the iWEF modelling tool

5.4 Concluding Remarks

There are multiple models, tools and indices available to evaluate and quantify the WEF nexus; most of these tools may, however, require modifications to be applicable to South Africa. Data availability and quality will be a factor in the reliability of the models, emphasising the necessity of a central database where data can be compared and justified. The issue of temporal and spatial scale differences between data also needs further inspection and may be resolved by integrating various models and tools.

6 CHAPTER 6: IDENTIFICATION AND DEVELOPMENT OF APPLICABLE METRICS AND INDICES FOR THE WEF NEXUS FOR SOUTH AFRICA

6.1 Introduction to WEF Nexus Metric and Indices

As discussed in Chapter 3, applicable metrics and indices (indicators) are important in operationalising the WEF nexus as they give a measure of the level of attainment (or shortfall) of the given WEF nexus resources securities. Simply put, metrics are standards or systems of measurement or quantification, and indices are a measure of the performance of something. Since the WEF nexus is all about synergies and trade-offs, metrics allow for the quantification of these and make them 'visible' and allow for comparisons, both post ante and ex ante scenarios. The choice and selection of metrics and indices depend on prevailing situations and circumstances, and their use (on non-use for that matter) thereof depend on individuals and institutional imperatives. In a practical sense, the application of metrics and indices is relative, and there is no 'one size fits all'. Metrics and indices range from highly technical measures through to soft measures in areas such as governance and social settings. The application of the WEF nexus as a natural resources management approach traverses this broad spectrum of issues, and likewise the applicable metrics. The important thing is to select metrics and indices that serve the purpose at hand.

With respect to this project, the purpose at hand is to use the WEF nexus as a tool for natural resources management and attain SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy) by 2030. Consequently the metrics and indices to be selected or developed must speak to these three SDGs at a minimum. Fortunately the SDGs have a whole range of indicators that are used as a measure to check if a given SDG target has been satisfied or met. The following sections discuss some of these indicators that speak more closely to SDGs 2, 6 and 7.

6.2 WEF Nexus Indices, Sustainable Development Goals (SDGs) and Sustainability Pillars

6.2.1 Link to SDG 2 (Zero hunger)

SDG 2 deals with ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture by 2030. It is a comprehensive SDG and an equally important one given that food insecurity and hunger are on the increase in the world, despite all the efforts that are being made. The targets and indicators for SDG 2 are given in Table 6.1 below.

Table 6.1: SDG 2 target and indicators (UN, 2016; UNSD, 2016)

Target Number	Target Description	Indicators
2.1	By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.	2.1.1 Prevalence of undernourishment. 2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES).
2.2	By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.	2.2.1 Prevalence of stunting (height for age <-2 standard deviation from the median of the World Health Organization (WHO) Child Growth Standards) among children under 5 years of age. 2.2.2 Prevalence of malnutrition (weight for height >+2 or <-2 standard deviation from the median of the WHO Child Growth Standards) among children under 5 years of age, by type (wasting and overweight).
2.3	By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.	2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size. 2.3.2 Average income of small-scale food producers, by sex and indigenous status.
2.4	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.	2.4.1 Proportion of agricultural area under productive and sustainable agriculture.
2.5	By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.	2.5.1 Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities. 2.5.2 Proportion of local breeds classified as being at risk, not at risk or at unknown level of risk of extinction.
2.a	Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries.	2.a.1 The agriculture orientation index for government expenditures. 2.a.2 Total official flows (official development assistance plus other official flows) to the agriculture sector.
2.b	Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round.	2.b.1 Agricultural export subsidies.
2.c	Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility.	2.c.1 Indicator of food price anomalies.

So with regard to the zero hunger SDG 2, the quest is for a set of indicators and metrics that capture the most and is all encompassing. Typically one is looking at food self-sufficiency and cereal productivity (as cereal is the staple of concern) under the pillars of accessibility, availability, affordability and stability. Concomitant with food security is the issue of nutrition security, concerned with intake of adequate nutrients for a healthy and active life. The argument goes that nutrition security encompasses food security, which encompasses nutrient content. Regarding nutrition security, the pillars are similar to food security as in food intake, accessibility, availability and affordability. The indicators of nutrition security tend to be indirect and measured through the most affected members of the population, those under the age of five years, by measuring the proportion of children that are stunted and or wasted or underweight.

6.2.2 Link to SDG 6 (Clean water and sanitation)

With respect to SDG 6 on ensuring availability and sustainable management of water and sanitation for all, the target and respective indicators are summarised Table 6.2 below. More importantly is the understanding and proper interpretation of the indicators for the SDG. The question that arises from the above is, for this research, what is the minimum set of indicators that can be applied as a measure of attaining SDG 6 in South Africa. As indicated in the sections below, for SDG 6, the indicators must capture water availability, accessibility and productivity under the pillars of affordability, stability and safety.

Table 6.2: SDG 6 target and indicators (UN, 2016; UNSD, 2016)

Target Number	Target Description	Indicators
6.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all.	6.1.1 Proportion of population using safely managed drinking water services.
6.2	By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.	6.2.1 Proportion of population using (a) safely managed sanitation services and (b) a hand-washing facility with soap and water.
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	6.3.1 Proportion of wastewater safely treated. 6.3.2 Proportion of bodies of water with good ambient water quality.
6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.	6.4.1 Change in water-use efficiency over time. 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources.
6.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.	6.5.1 Degree of integrated water resources management implementation (0–100). 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.	6.6.1 Change in the extent of water-related ecosystems over time
6.6a	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.	6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan.
6.6b	Support and strengthen the participation of local communities in improving water and sanitation management.	6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management.

6.2.3 Link to SDG 7 (Affordable and clean energy)

SDG 7 deals with ensuring access to affordable, reliable, sustainable and modern energy for all. It is important to note that the SDG flags sustainable modern energy for all. So the question arises as to whether energy sources such as firewood or coal or peat are sustainable and modern enough to be considered in this goal, or is modern and sustainable only reserved for renewable energies such as solar and wind power. The targets and indicators for SDG 7 are given in Table 6.3 below.

Table 6.3 SDG 7 target and indicators (UN, 2016; UNSD, 2016)

Target Number	Target Description	Indicators
7.1	By 2030, ensure universal access to affordable, reliable and modern energy services.	7.1.1 Proportion of population with access to electricity. 7.1.2 Proportion of population with primary reliance on clean fuels and technology
7.2	By 2030, increase substantially the share of renewable energy in the global energy mix.	7.2.1 Renewable energy share in the total final energy consumption.
7.3	By 2030, double the global rate of improvement in energy efficiency.	7.3.1 Energy intensity measured in terms of primary energy and GDP.
7.a	By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.	7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems.
7.b	By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states and landlocked developing countries, in accordance with their respective programmes of support.	Investments in energy efficiency as a proportion of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services.

As with food and water security, what are the indicators applicable to SDG 7 on energy security? The indicators of concern would include accessibility and productivity of energy under the pillars of reliability, sufficiency, and energy type. The issue of energy type is important, and so is the source of the energy. An interesting example for a country like South Africa is indicator 7.1.1 on 'Proportion of population with access to electricity', although the proportion might be high, the source of the electricity energy (coal fired power stations) is certainly not considered modern, and hence not sustainable in the long run. This is why when one is dealing with these targets and indicators, one takes them in their full context and not be selective as that might give the wrong interpretation and conclusion.

6.3 Selected WEF Nexus Indices for South Africa

In selecting WEF nexus indicators for this research, use is made of outputs from other WRC funded research. In this case, the two reference research are those by Nhamo et al. (2020) and Simpson et al. (2019) which set out to define and develop a set of WEF nexus indicators applicable at various spatial and temporal scales. The work by Nhamo et al. (2020) developed indicators that are tied to drivers of natural resources securities of availability, accessibility, self-sufficiency and productivity. The same drivers also speak to the economic, social and environmental dimensions of sustainability. Although the WEF nexus indicators seem to cover the water, energy and food sectors, they are somewhat quiet on nutrition security. The WEF Nexus Indicators of Simpson et al. (2019) do speak to nutrition security, as it is an important component of food security.

The minimum set of WEF nexus indicators proposed for this research are indicated in Table 6.4. Also in the table is the direct link to specific SDGs and the spatial and temporal scales. Over and above the indicators in Table 6.3 above, other indicators considered fall under health and environment and include;

- The proportion of population using safely managed drinking water services
- The proportion of bodies of water with good ambient water quality
- Mortality rate attributed to unsafe water, sanitation, and poor hygiene
- Forest area as a proportion of the total land area
- The proportion of land that is degraded over total land area
- Prevalence of malnutrition
- Biodiversity extent/hotspots

6.4 Concluding Remarks

In summary, the selected WEF nexus indicators adequately cover the SDGs 2, 6 and 7 both in space and time. Two indicators each for SDGs 6 and 7 have been selected, respectively answering to the pillars on affordability, stability and safety and then reliability, sufficiency and energy type. With respect to SDG 2, four indicators have been selected answering the pillars on accessibility, availability, affordability and stability. Coupled with these, another three indicators have been selected to cover nutrition dealing with the food intake, accessibility, availability and affordability pillars. Over and above these, other indicators considered fall under health and environment to cater for water, health, energy and nutrition (WHEN) and water, energy, food and ecosystem (WEFE) nexus.

Table 6.4: Minimum set of indicators for SDGs 2, 6 and 7 (adapted from Nhamo et al., 2020; Simpson, 2020)

Sector	Indicator	Units	Pillars	Spatial Scale			Temporal Scale			SDG Indicators
				Local	Provincial/ catchment	National	Past	Present	Future	
Water	Proportion of available freshwater resources per capita (availability)	m^3/cap	Affordability Stability Safety		X	X	X	X	X	6.4.2
	Proportion of crops produced per unit of water used (productivity)	\$/m^3		X	X	X	X	X	X	6.4.1
Energy	Proportion of the population with access to electricity (accessibility)	%	Reliability Sufficiency Energy type			X	X	X	X	7.1.1
	Energy intensity measured in terms of primary energy and GDP (productivity)	MJ/GDP				X	X	X	X	7.3.1
Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency)	%	Accessibility Availability Affordability Stability	X	X	X	X	X	X	2.1.2
	Food Consumption Score (FCS)	%		X	X	X		X		2
	Human Dietary Diversity Score (HDDS)	%		X	X	X		X		2
	Proportion of sustainable agricultural production per unit area (cereal productivity)	kg/ha		X	X	X	X	X	X	2.4.1
Nutrition	Proportion of stunted pre-school (under 5 years) children	%	Food intake Accessibility Availability Affordability	X	X	X		X		2.2.1
	Proportion of wasted pre-school (under 5 years) children	%		X	X	X		X		2.2.2
	Proportion of underweight pre-school (under 5 years) children	%		X	X	X		X		2.2.2

7 CHAPTER 7: DEVELOPMENT OF A BLUE-PRINT FOR PACKAGING THE WEF NEXUS TO REALISE SDGs 2, 6 and 7

7.1 Introduction

To date, the WEF nexus is fairly well understood although its wider application is somewhat limited. Heads of arguments have been put forward as to why there is limited uptake and application of the WEF nexus as a natural resources management tool to ensure water, energy and food resources securities. Some of the reasons include; limited understanding of the concept in some cases, limited technical skills required for its application, lack of appropriate models or tools, scepticism in some quarters about the WEF nexus, complex interactions among the stocks and flows of water, energy and food, or even lack of or poor packaging of the WEF nexus. This chapter deals with aspects of the WEF nexus and its packaging for application at the local, provincial and national. The term packaging is meant to highlight the developmental stages and consequent application of the WEF nexus to attain SDGs 2, 6 and 7. The arguments start with linking nexus planning and SDGs 2, 6 and 7, and then discuss data issues and finally the potential application of the WEF nexus at the different levels.

7.2 Linking Nexus Planning and SDGs 2, 6 and 7

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, and (iv) periodic assessment and monitoring of SDGs performance, and (v) benefits of regular SDGs monitoring (Figure 7.1). A water-energy-food nexus integrative model was adopted in this study (Nhamo et al., 2020). 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., 2020). By establishing the numerical relationships between distinct indicators, the model identifies areas needing immediate intervention to balance resource use and achieve sustainable management. Establishing each indicator's indices for a particular period provides pathways to assess progress towards SDGs as nexus indicators are the same SDG indicators.

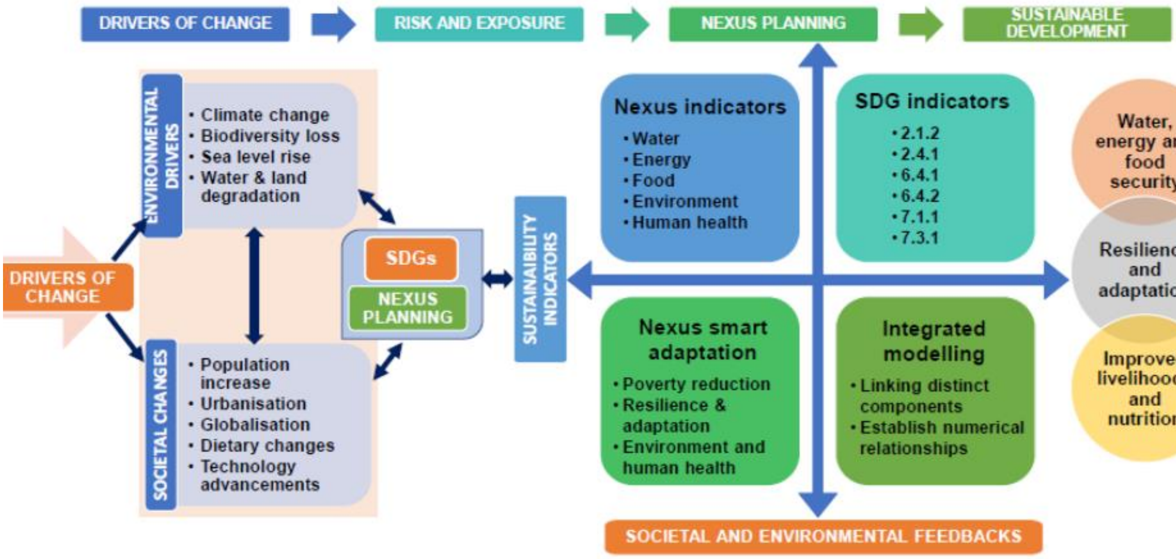

Figure 7.1 Conceptual framework linking nexus processes with Sustainable Development Goals (SDGs).

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 (Figure 7.1). This facilitates an understanding of how socio-economic, environmental, and ecological interactions influence negative change, and ultimately unsustainability. The processes unravel societal and ecological outcomes affected by these interactions (food security, ecosystem services and social welfare), which are best explained through sustainability indicators (Nhamo et al., 2020). 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 7.1).

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 a set of indicators formulated around resource utilisation, accessibility and availability (Nhamo et al., 2020). Nexus modelling develops knowledge-based tools to assess vulnerability and resilience, promoting interventions that enhance healthy human-environment interactions. The tools facilitate identifying pathways for simultaneous resource security and conservation through an analysis of societal and environmental feedback (social, ecological, political, and economic determinants).

7.2.1 WEF Nexus analytical tool

The WEF nexus analytical tool has been discussed already in Chapter 5 (sub-section 5.5.1). Suffice to mention is the importance of integrating indicator indices (sub-section 7.2.2) with the WEF nexus analytical tool. The WEF nexus analytical model manages to establish relationships among different, but linked WEF sectors, moving the WEF nexus approach from a theoretical framework to an analytical and practical one that provides real world solutions. The analytical model enables the evaluation and management of synergies and trade-offs in resource planning and utilisation.

7.2.2 WEF Nexus sustainability indicators

WEF nexus sustainability indicators are measurable parameters that are directly linked to the WEF nexus, and measure the performance of the utilisation and management of water, energy and food resources. Selected measurable sustainability indicators for WEF nexus performance are those that are related to resource availability, accessibility, self-sufficiency and how these influence respective production (productivity) (Table 7.1). Resource availability, accessibility, self-sufficiency and productivity are the major drivers of the securities of water, energy and food from where indicators are defined. Any other indicators that do not relate to these drivers are excluded from the list of WEF nexus indicators. As the same drivers are also key in the securities of water, energy and food, the defined WEF nexus sustainability indicators should also evolve around resource availability, accessibility, self-sufficiency and productivity, key drivers in resource management. The same drivers are also crucial in sustainability dimensions that include economic (increasing resource efficiency), social (accelerating access for all), and environmental (investing to sustain ecosystem services). Thus, the main criteria used to define and select WEF nexus indicators were (i) any indicators available in literature that referred to water, energy and food resources, but (ii) were not directly linked to the nexus and its drivers, or (iii) were not key to WEF securities, were excluded from the list of WEF nexus indicators. However, the selection of indicators is dependent on the characteristics of each particular place and can always be adjusted.

Within each WEF nexus sustainability indicator are pillars that sustain the indicators. These pillars also play an important role when establishing numerical relationships among indicators, but fall short of being WEF nexus indicators according to the set criteria. Each WEF nexus sector has its set of indicators and pillars that are used to establish quantitative relationships within the WEF nexus. For example, a country may have abundant water resources per capita (availability), but may not be affordable for the majority of the population or accessible to many as supplies from the sources may not be stable due to systems failures (stability). Furthermore, a country may have sufficient energy supplies, but they are not reliable or the energy type is condemned. All these factors were considered when establishing indicator relationships.

The selected WEF nexus indicators and pillars (Table 7.1) can be adopted anywhere, as they are the same indicators used for the SDGs (https://unstats.un.org/sdgs/metadata/). Country baseline data for the indicators is collected from World Bank indicators or from national statistical offices.

Table 7.1 Sustainability indicators and pillars for WEF nexus sectors.

Component	Indicator	Units	Pillars
Water	Proportion of available freshwater resources per capita (availability)	m^3/capita	Affordability Stability Safety
	Proportion of crops produced per unit of water used (productivity)	US$/$m^3$	
Energy	Proportion of the population with access to electricity (accessibility)	%	Reliability Sufficient Energy type
	Energy intensity measured in terms of primary energy and GDP (productivity)	MJ/GDP	
Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency)	%	Accessibility Availability Affordability Stability
	Proportion of sustainable agricultural production per unit area (cereal productivity)	Kg/ha	

7.2.3 Linking nexus planning and related SDGs indicators

The nexus's value is its documentation of the cross-sectoral and integrated management of resources and simplifying intricate interlinkages between distinct sectors or components of a system. Nexus planning is meant 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., 2019a; Nhamo et al., 2020). An integrated smart attribute of nexus planning is identifying different interventional priorities to enhance sustainability (Nhamo et al., 2020). The approach is directly related to SDGs in that both are concerned with resource sustainability and security, and the former provides tools to assess progress towards SDGs. The linkages between nexus planning and SDGs are further cemented by using indicators as guiding instruments to either assess progress in implementation or establish numerical relationships between distinct sectors/components (Bizikova et al., 2014). Nexus planning sustainability indicators are directly linked to related SDG indicators; they are vital for evaluating SDGs implementation progress (Nhamo et al., 2020). Both the 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 7.1 lists nexus planning indicators, as well as the related SDG indicators.

We establish the relationships between SDGs and two nexus types: the water-health-environment-nutrition (WHEN) nexus and the water-energy-food (WEF) nexus. SDG indicators directly linked to both the 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 (Table 7.2). The focus is on indicators directly falling under the WHEN and WEF nexuses frameworks on ensuring water, energy and food security, improving efficiency in resources management to attain sustainability, and ensuring human and environmental health (Liu et al., 2018). These nexus planning attributes link the approach to SDGs 2, 3, 6, 7 and 15.

Table 7.2 WEF nexus indicators and pillars, and the linked SDG indicators

Nexus type	**Sector**	**Nexus planning indicator**	**SDG indicator**
	Water	Proportion of crops/energy produced per unit of water used Proportion of available freshwater resources per capita	6.4.1 6.4.2
WEF	Energy	Proportion of 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 Proportion of sustainable agricultural production per unit	2.1.2 2.4.1
	Water	Proportion of population using safely managed drinking water services Proportion of bodies of water with good ambient water quality	6.1.1 6.3.2
WHEN	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 Proportion of land that is degraded over total land area	15.1.1 15.3.1
	Nutrition	Prevalence of moderate or severe food insecurity in the population	2.1.2 2.2.2

From the review of the link between the nexus and the related SDGs, the relationship between the two can be summarised as follows:

- The approach is directly related to SDGs in that both are concerned with resource sustainability and security, and the former provides tools to assess progress towards SDGs
- The linkages between nexus planning and SDGs are further cemented by using indicators as guiding instruments to either assess progress in implementation or establish numerical relationships between distinct sectors/components (Bizikova et al., 2014).
- Nexus planning sustainability indicators are directly linked to related SDG indicators; they are vital for evaluating SDGs implementation progress (Nhamo et al., 2020).
- Both the 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.

7.2.4 Periodic assessment and monitoring of SDGs performance

Periodic assessment and monitoring of the SDGs performance is an important aspect of the WEF nexus application. As covered above, the WEF nexus sustainability indicators are anchored in sustainability pillars that support the indicators for water, energy and food which speak directly to the SDGs indicators, namely, 6.4.1 and 6.4.2 for water, 7.1.1 and 7.3.1 for energy and 2.1.2 and 2.4.1 for food). With the WEF nexus analytical model, the applicable WEF nexus indicators are determined on a regular basis and used to monitor performance towards meeting the SDGs 2, 6 and 7. The progress made in towards meeting the target SDGs is used to formulate policy and allocate as well as manage resources for a hastened attainment of the SDGs.

7.2.5 Benefits of regular SDGs monitoring

Regular monitoring is beneficial simply because it informs the policy makers and the operatives of how much progress has been made towards attaining or meeting the SDGs over a period of time. This could be against set targets to be met by a given time period. Monitoring keeps everything under surveillance or spotlight. Without regular monitoring it is near impossible to know if progress would have been made towards achieving the SDGs 2, 6 and 7.

7.3 Data Sources and Availability

The recognition of the importance of the WEF nexus as a decision support tool to assess SDGs' progress has gathered momentum worldwide. However, the main obstacle to achieving this has been data unavailability. Data availability is central in informing and weighting indicators during the PCM process (Nhamo et al., 2019). Even where data could be available, it is normally heterogeneous (Zuech et al., 2015). Data uniformity is necessary mainly for comparison purposes, particularly between countries (Liu et al., 2017). The variations in data collection and storage bring a host of challenges, including data disparity, mismatch, and a 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 (Giuliani et al., 2017; Makapela et al., 2015). For example, the Landsat Mission provides uninterrupted land and atmospheric information backdating 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 interlinkages between the WEF sectors, and assess progress in implementing the SDGs (Mabhaudhi et al., 2019b). 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 the fusion of data obtained or derived at different spatial and temporal scales, or from different satellites (Huang et al., 2018).

7.4 WEF Nexus at the National Level – Strategy and Policy Instrument/Issues

The strength of the WEF nexus as a natural resources management tool to attain the water, energy and food securities lies in its ability to integrate these at different spatial and temporal scales. At the national level, the WEF nexus enables policy makers to assess the performance of the selected WEF nexus indicators, principally, water (water availability and water productivity), energy (energy accessibility and energy productivity) and food (cereal productivity and food self-sufficiency). With such knowledge, policy makers and national strategists can decide how best to deploy national resources to attain an acceptable balance of the WEF nexus indicators in water, energy and food (see Chapter 8, sub-section 8.6.2.4). The WEF nexus analytical model has successfully been applied at this level, including even at the SADC region.

7.5 WEF Nexus at the Provincial Level – Integrative Analytical Model Application

At the provincial level, the WEF nexus is equally applicable. As indicated elsewhere in this report, the boundaries of application of the WEF nexus can be defined to suit the purpose at hand, i.e. could be administrative or geographic (basins and catchments). In South Africa administrative boundaries may be preferred because developmental resources are allocated from the national coffers down to the provincial level (see Chapter 8, sub-section 8.6.2.3). The analytical model has previously been applied at this level.

7.6 WEF Nexus at the Local Level – Integrative Analytical Model Application

At the local level, defined from smallest or lowest unit up to district or municipal scale, this is characterised by the movement of resources, good and services across the selected boundaries (see Chapter 8, sub-sections 8.6.2.1 and 8.6.2.2). The WEF nexus is equally applicable at this scale, although developmental resources will be coming from the provincial and national coffers. The analytical model has successfully been applied at this level.

More on the WEF nexus at the local level, provincial level and national is given in the final report of a sister project funded by the WRC, project number CON2019/2020-00007 titled "*FROM THEORY TO*

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

7.7 Concluding Remarks

In conclusion, South Africa just like many other countries in the world believes that the WEF nexus can be used as a tool to attain SDGs 2, 6 and 7. This means the nations needs the WEF Nexus to be properly packaged for this. The whole process commences with linking WEF nexus planning with the target SDGs and this encompasses five thematic themes, these are; description of nexus analytical tool, defining WEF nexus sustainability indicators, linking nexus planning and related SDGs indicators, periodic assessment and monitoring of SDGs performance, and lastly benefits of regular SDGs monitoring. The WEF nexus is literally applicable at all spatial scales – from local through to regional scale.

8 CHAPTER 8: ANALYSIS AND DEVELOPMENT OF MODALITIES FOR UPSCALING, OUTSCALING AND DEEPSCALING THE WEF NEXUS IN SOUTH AFRICA

8.1 Introduction

Worldwide the demand for water, food and energy is increasing due to rapid population and economic growth in concert with accelerated urbanisation and changing lifestyles. It is projected that by 2030 the global population will need at least 40% more water, 35% more food and 50% more energy. By 2050, a 70% increase in global food demand is predicted. Meeting the demand for food in sufficient quantities and acceptable nutritious quality underlines the importance of greater efficiencies in agricultural production systems globally (using water and energy). It is projected that by 2025, 40% of the global population will be prone to severe water stress – both physically and economic water stress. According to the UN SDG report 2018, water insecurity remains high and accelerated progress is needed to meet the Sustainable Development Goals (SDGs) 2 (zero hunger) and 6 (clean water and sanitation). Global energy demand is projected to rise by 25% until 2040, hence putting into doubt the attainment of SDG 7 (affordable and clean energy).

It is against this background that the WEF nexus came to the fore as a viable decision support tool, that among other things; indicates the performance of resource utilisation and planning, establishes a quantitative relationship among interlinked resources, and indicates priority areas for intervention, aimed at establishing a balanced resource use and planning, and inclusive economic growth for sustainable development (Nhamo et al., 2020). Thus, the method is a catalyst for climate change adaptation and resilience-building by improving human well-being and attaining Sustainable Development Goals (SDGs), particularly SDGs 2, 6, and 7 (Mabhaudhi et al., 2019a; Mpandeli et al., 2018).

In South Africa, water, energy, and food security form the basis of a resilient economy (Von Bormann and Gulati, 2014) and sustainable and inclusive development. The challenges South Africa faces concerning water, energy, and food securities make it imperative that future development are anchored in WEF nexus approaches. Thus, the operationalisation of the WEF nexus at various spatial and temporal scales within South Africa can address the challenges related to water, energy, and food resource insecurities (Mabhaudhi et al., 2016a; Nhamo et al., 2018).

8.2 The WEF Nexus Contextualised

As with any new concept or innovation, the WEF nexus finds itself with many 'faces' as it is understood differently by different users and its diverse utility. The WEF nexus has been called a concept, a conceptual framework, an analytical tool, a discourse, an innovation and even a practice. Worldwide the WEF nexus has been applied to a wide range of cases, both in space and in time. Despite its popularity, as evidenced by the exponential growth in research publications to do with the WEF nexus, its wider uptake and application have remained fairly low. It has generally been applied only on a case study basis. There is no evidence of wholesale mainstreaming of the WEF nexus as a planning tool for natural resources management. The question that arises then is, why? It is thus imperative that we understand what needs to be done to up-scale and out-scale the WEF nexus as a tool – what are the requirements for the successful scaling of the WE nexus in South Africa and elsewhere, both in space and in time? How can we move from mere rhetoric about the WEF nexus to mainstreaming it as a planning tool?

8.3 Impediments to WEF Nexus Uptake in South Africa

There are several impediments to the uptake and adoption of the WEF nexus, mainly in the application. Table 8.1 summarises some of the key issues and challenges to the uptake of the WEF nexus.

Needless to mention, factors that hinder the uptake of the WEF nexus into practice vary in space and time and are situational. An interesting anecdote to this is the need to fully appreciate and understand these impeding factors before discussing scaling up/out the adoption of the WEF nexus as a tool for sustainable natural resources management. The next chapter of this report discusses the issues of up-scaling, out-scaling and deep scaling the WEF nexus as technology and practice.

Table 8.1: Summary of issues and challenges to the uptake of the WEF nexus

Level	Issue/(s)	Challenges
Research /scientific	Conceptualisation	• The complexity of the WEF nexus systems and their related frameworks, tools, models and data requirements
	Improving understanding of the interlinkages between WEF resource and sector	• Lack of understanding of the interlinkages between the WEF resource and sectors • lack of analytical tools to help understand the interlinkage between the WEF nexus elements and sectors
	Development of frameworks, tools and models	• Lack of data to test and validate the WEF nexus tools
	Testing of tools/ models and frameworks	• Lack of quality data with appropriate spatial and temporal scale
	Documentation of what works (case studies of best WEF nexus practices)	• Studies are fragmented, with researchers approaching it from a "comfort zone" • Context-specific nature of WEF nexus solutions/ intervention makes it harder to derive specific WEF nexus best practise with a comprehensive catalogue of methods, tools and approaches
	Documentation of context (methods, tools and approaches) used in case studies (this would guide the selection of tools, models and	• Case studies have a regional relevant • The context-specific nature of WEF nexus interventions hinders the development of a comprehensive catalogue of methods, tools and approaches
National/policy	From theory to practice	• Bridging the science-policy gab – a case of "easier said than done"
	Dialogue	• This need to be supported by scientific evidence (with tools still lacking, this is also still lacking)
	Disjointed policy and decision making	• Policymaking processes remain fragmented • Insufficient incentives for integrated planning and policymaking at all levels, and limited vision
Local/implementation	Raising awareness	• Dissemination of information is still lacking (this could be because the implementation of the WEF nexus is only beginning) • Lack of incentives for private sectors to spread the WEF nexus relevant projects
Other considerations	Persuasion (communication of the potential impact or benefits of applying the WEF nexus approach)	• Lack of practical evidence of WEF nexus application to motivate adoption
	Enabling environment	• Fragmented institutions (WEF sectors still operating in "silos"
	• Fragmented institutions (WEF sectors still operating in "silos"	• While expert knowledge of each sector remains relevant, integrated knowledge (incorporating all three sectors) is needed
	How to implement	• Lack of practical experience to guide successful implementation • Lack of guidelines of how to put the WEF nexus into use

8.4 Upscaling, Outscaling and Deep Scaling Defined and Contextualised to the WEF Nexus

In general, scaling refers to the process of increasing the number of people benefiting from a technology or a practice. For example, this could mean getting a set of principles, or a methodology adopted more widely, replicating a programme or intervention in new areas or attracting more customers or users for a product or service. Not all technologies, innovations or practices are scalable. Usually, scaling is considered when perceived potential that the technology or practice would benefit a wider population. Other factors to consider when scaling a technology or practice include the cost of adopting the technology (this answers the question, compared to other or current technologies, and is it better?). Once a decision to scale technology or practice has been made, it is crucial to decide which elements of the technology or practice to scale. Scaling can be done at different stages of the programme or project. The following subsections provide a brief description of the different types of scaling: up-scaling, out-scaling, and deep scaling. In this report, up-scaling is used synonymously with scaling up and out-scaling with scaling out. An important point to note is that, temporally, scaling time frames can range from a couple of months to decades, depending on the innovation or practice or concept or program under consideration.

In short, up-scaling (or scaling up), out-scaling (or scaling out) and deep scaling (or scaling deep) deal with impacting laws and policy, impacting greater numbers and impacting cultural roots, respectively. Figure 8.1 displays the definitions of up-scaling, out-scaling and deep scaling (Riddell and Moore, 2015). Out-scaling serves the purpose of raising awareness about the innovation. In contrast, up-scaling tackles the institutional barriers that might get in the way of scaling an innovation/technology, and deep scaling aims to affect doing things in a certain social context (Riddell and Moore, 2015; Westley et al., 2014). Each of these terms is discussed briefly in the following subsection.

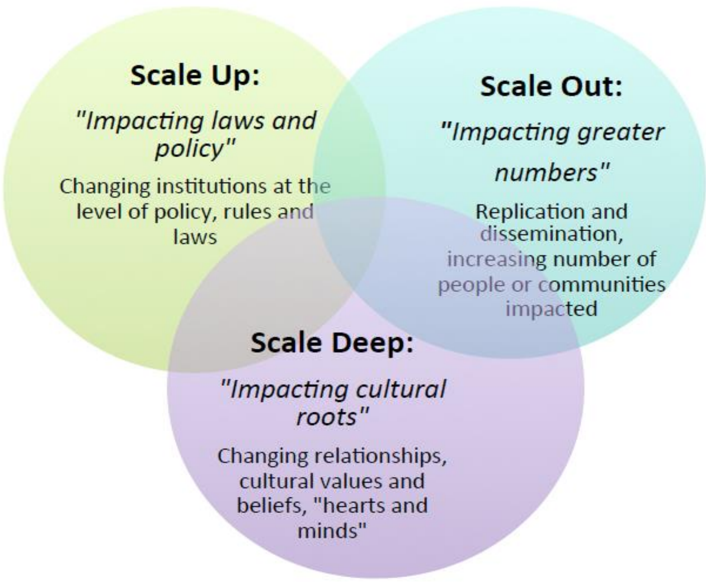

Figure 8.1: Definitions of scaling up, scaling out and scaling deep (after Riddell and Moore, 2015)

8.4.1 Up-scaling

By up-scaling, we mean a process for significantly increasing the number of sustained implementations of a successful program, thereby serving more people with comparable benefits. Up-scaling consists of both vertical and horizontal, the former referring to institutionalisation and the latter referring to adoption. Horizontal scaling refers to an increase in the reach of innovation by expansion or replication within or across jurisdictions (Butler et al., 2020). Horizontal scaling means spreading the innovation geographically (number of people adopting the technology). Vertical scaling refers to expanding the impact of innovation through policy, regulatory or institutional reform at a higher organizational level. Vertical scaling involves facilitating the harmonization of policies or laws to instil vertical scaling within or across countries. Other types of scaling up are explained in Table 8.2.

Table 8.2 Description of other forms of scaling up (adopted from Gundel et al. (2001))

Unwin's terms	**Description**	**Alternative terms**
Quantitative scaling up	"Growth" or "expansion" in their basic meaning: increase the number of people involved through replications of activities, interventions and experiences	Dissemination, replication
Functional scaling up	Projects and programs expand the types of activities (e.g. from agricultural intervention to health, credit, training, etc.)	Scaling out or horizontal scaling up
Political scaling u[	Projects/programs move beyond service delivery, and towards change in structural/institutional changes	Vertical scaling up
Organizational scaling up	Organizations improve their efficiency and effectiveness to allow for growth and sustainability of interventions, achieved through increased financial resources, staff training, networking, etc.	Vertical scaling up institutional development

**Note: (a) represents terms adopted from Uwin (1995) while (b) represents terms adopted from Gundel* et al. *(2001)*

8.4.2 Out-scaling

Out-scaling occurs when an organisation/(s) driving the technology or innovation through replication, diffusion, and dissemination attempts to affect or impact more people and cover a large geographical area. Out-scaling occurs when innovators aim to address a problem's broader institutional or systemic roots (Westley et al., 2014). In essence, out-scaling can be likened to horizontal scaling in the preceding section.

8.4.3 Deep scaling

Deep scaling is an attempt to spread the changes in relationships, mindset, cultural values and beliefs through technology or innovation. Approaches such as the WEF nexus aims to change the status quo, which is moving from managing the WEF resource in "silos" to managing in a more integrated and multi-centric manner. Such change requires a change in mindset, cultural values and beliefs of those involved in allocation, management and utilisation. This methodology might be appreciated in facilitating stakeholder buy-in from the WEF sectors.

8.4.4 Other scaling

As alluded to earlier, out-scaling and up-scaling lend themselves to varied definitions, often leading to confusion and misunderstanding of the concepts. Sometimes the differences are conceptually fundamental, and at times they are language and purpose-based. Clear definitions must be provided to assist in understanding the context that it will be applied whenever scaling is discussed. Daily, we deal with scaling issues, ranging from agricultural practices through water technologies to medical and health innovations, such as vaccinations.

8.5 Selected Upscaling and Outscaling Approaches

This section provides an outline and discussion of the common up-scaling and out-scaling methodologies. These methodologies include, but are not limited to (a) Communication Pathways Approach (b) Theory of Change Approach (c) Diffusion of Innovation Approach (d) Trickle-down or Trickle-up Approach (e) Nudge Theory Approach (f) Pathways to Impact Approach and (g) Soft Systems Methodology.

8.5.1 Communications Pathway Approach (CPA)

Communication Pathway Approach (CPA) identifies the right pathway/(s) for scaling technology or practice. In communications pathways language, the process begins with a "sender" developing or generating or creating a 'message', then sending the message through a "pathway or channel" to a target "receiver" (Valenzo et al., 2015). In this case, the message is the (WEF nexus) innovation or practice. The choice of pathways for scaling technology is guided by the profile of the technology, the resource and capacities required for successful launch and scale, and the personalities and preferences of those leading or driving the scaling of the technology. Along the pathway, the message will invariably encounter physical and/or psychological 'noise', or anything that interferes with the target receiver's ability to properly receive the message (Valenzo et al., 2015). Typical psychological noises include; prejudice or ill will toward the innovation, preoccupation with other thoughts, emotional reaction to the innovation/practise, unwillingness or obstinacy to be open-minded about new developments, and simple resistance to the message. As previously stated, all these potential noises have to be overcome before the message can get across.

There are various pathways or business models which can be adopted in scaling a technology or practice. Innovations or technologies developed by a single organisation or entrepreneurs often follow the following pathways, organisational growth with selective outsourcing, multi-stakeholder partnerships, licensing out the technology, affiliations and partnerships. For technologies developed through research and disseminated to the end-users tend to rely heavily on creating networks (for exchanges of information) as a pathway for scaling. Those leading the scaling of the technology would assess the situation and decide on the most appropriate pathway. Each pathway achieves different results depending on the context in which they are applied. However, the right choice of pathway influences the scaling of the technology further down the road. To enhance the chance of achieving a broader impact, it is important to understand possible options in the early stages of scaling a technology and make deliberate decisions at the right time.

The financial, technical, human, and other resources required for scaling a technology make it difficult for a single organisation to undertake to scale. Hence, pathways are not to identify the best model with the technology but rather to access the resources and partnerships required for successful scaling. Therefore, successful scaling of the technology is dependent on organisations working together to access resources, how those organisations work together and when those organisations enter into a collaborative arrangement. In a recent development, Senzanje et al. (2021) have proposed the Communications Pathway Approach as a possible way to up-scale. They out-scale the WEF nexus in South Africa and the region. This is still a work in progress. More needs to be undertaken to properly prepare the 'message', create or generate the right 'pathways' and prepare the 'receivers' to be ready for the WEF nexus message. Already, substantial noises include cynicism towards the WEF nexus, operational resistance from some concerned parties, lack of clarity of the innovation/ practice, and psychological fatigue to innovation so soon after IWRM of suitable models applicable to the country and the like. These must be overcome before the WEF nexus can become part of the daily operational tools used in integrated natural resources management.

One of the main assumptions made in the communication pathways approach is that each innovation or technology is developed to scale. Not all innovations/technologies are scalable. Often time the decision to scale the technology is made in a later stage of the technology.

8.5.2 Theory of Change Approach (ToC)

A Theory of Change (ToC) approach is defined broadly by Weiss (1995) as a theory of how and why an initiative works. A ToC is also described as a model that addresses pathways of change and how those changes are expected to occur (ex-ante case) or how change has occurred (ex-post case) (Mayne, 2017). A more operational definition of ToC is a participatory planning process involving key stakeholders. It aims to understand the process of changes by mapping out intermediate and long-term outcomes on a causal pathway. Others added that ToC is a systematic and cumulative study of the links between activities, outcomes, and contexts of the initiative. A good ToC is plausible, doable and testable. In general, ToC aims to bring stakeholders from various organisations or sectors to work on common short-term, medium-term and long-term goals. ToC does not provide a guide for selecting participants or stakeholders to map out the long-term outcome.

The organisation leading the development of ToC run workshops to get the participants to understand the long-term impact aimed to be achieved. Once the goals have been set, participants work out a step by step strategy to achieve the goals. Assumptions are made and tested against reality. If applied in scaling a technology, a ToC would document the impact of the technology and seek to understand and document all the intermediates steps to ensure that activities and resources are aligned with the said change.

The main strength of the ToC lies in its ability to foster accountability and awareness about the potential challenges that an organisation or stakeholders might encounter while perusing the mission. Developing a theory of change, which articulates long-term goals and intermediate outcomes and assumptions about how they will be achieved, is a good way of setting a focus.

Interesting, worth noting and of current relevance to South Africa is a recent publication by Naidoo et al. (2021). They proposed and attempted to practicalise the operationalisation of the WEF nexus in the country through the Theory of Change approach. They posit that the consultative and iterative Theory of Change culminated with the formulation of pathways to overcome the barriers impeding WEF nexus operationalisation, mitigation of trade-offs while enhancing synergies towards attaining simultaneous resource securities, poverty alleviation and reduction of inequalities, and reconciling policy with implementation scale.

8.5.3 Diffusion of Innovations (DoI)

Diffusion of Innovation (DOI) is a social science theory that originated in communication to explain how over time, an idea, technology or product gains momentum and diffuse (spread) through a specific population or social system. In diffusion of innovation, Rogers (1995) defined diffusion as the social process by which an innovation is communicated through certain channels over time among a social system. The result of the diffusion is that people, organisations, or groups as part of a social system adopt the new idea, behaviour, practice, or technology. It is said that the key to adoption is that the person must perceive the idea or behaviour to be new or the technology or product to be innovative. Adoption of new ideas does not happen simultaneously for all people. Rogers (1995) classified consumers as a group of adopters based on their demographic and psychographic features, into five categories or segments which are namely, innovators, early adopters, early majority, late majority, and laggards, according to how they successively adopted the innovation through the stages of the product life cycle (see Figure 8.2). Moore (2004) extended this classification by classifying adopters as technology enthusiasts, visionaries, pragmatists, conservatives, and sceptics, who sequentially adopt the innovation as the product life cycle progresses.

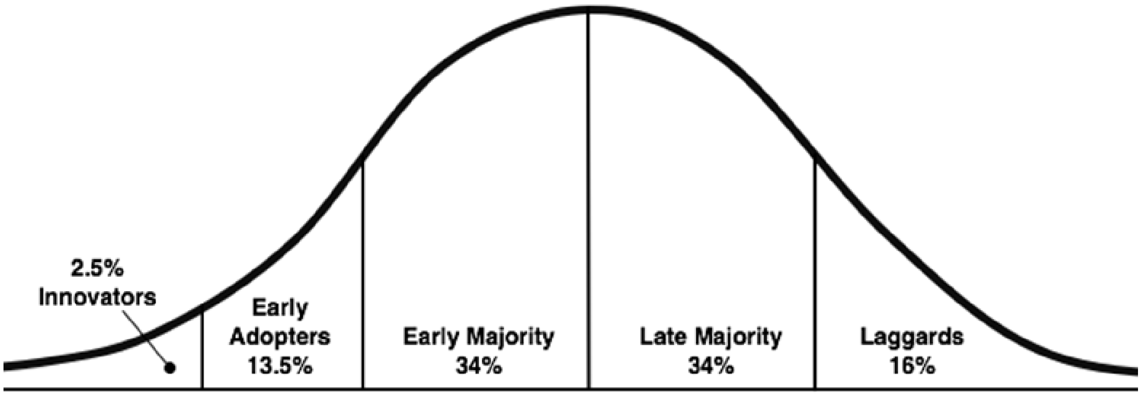

Figure 8.2 Classification of adopters based on demographic and psychographic feathers (Adopted from Rogers 1995)

The diffusion of innovation indicates how new ideas spread in a social system. The key question remains, how can diffusion of innovation be increased or improved? According to Hagerstand's conceptualisation of innovation diffusion, adoption occurs due to the learning and communication process. The adoption rate or speed of diffusion of an innovation or technology is determined by the innovation's characteristics, including the relative advantage, compatibility, complexity, trialability, divisibility, and observability.

Those applying the DOI for scaling up a technology need to select appropriate communication channels to link with the target social group. Table 8.3 displays communication channel options and highlight some advantages and disadvantage of each option.

Table 8.3 Communication channels options

Communication channel	**Advantages**	**Disadvantages**
Face-to-face setting with the target audience	The most effective way to diffuse	Impractical and too expensive
Mass media	Less expensive	One cannot be sure that one's message truly reaches the intended target
Electronic messaging via the Internet	Easier to obtain feedback from the target audience	Internet and www capabilities require the development and application of new concepts and models for diffusing and marketing products and services

The DOI has been extensively studied and applied in all spheres of society, ranging from social settings to highly technical ones.

8.5.4 Trickle Down/Trickle Up Approach

Sometimes it is impossible to reach all target audiences meant to be reached by a technology simultaneously. This could be because of the lack of necessary financial and human resources required to reach the targeted population. The trickle-down approach focuses on building capacity in a portion of the population (e.g. top-level), hoping that the impact or benefits, even knowledge of a technology, trickle down to the rest of the target population through diffusion (Dixon, 2013).[3] On the same note, the Trickle-up approach focuses on members of the lower level with the hope that impact, benefits, or knowledge will trickle up through diffusion.

The effectiveness of this method has been questioned in the literature (Qureshi, 2008). Some of the concerns emanate from the fact that there is no way of knowing if the benefits will diffuse, which benefits will diffuse and at what rate? Typically, the better the interconnectedness of the different 'layers' in the trickle-down setup, the better the chances of realistic trickling-down of an innovation or practice. It has been noted that if cost is a major hindrance for scaling a technology or practice, a trickling-down and trickling-up approach could be a viable option (Rice and Sheridan, 2014). This approach tends to work when a single organisation leads the scaling of a technology.

8.5.5 Nudge Theory Approach

The Nudge Theory Approach (NTA) is based on the Nudge theory, which is a concept for understanding peoples' thinking, decisions and behaviour to help them improve their thinking, decisions, manage a change of all sorts and identify and modifying existing unhelpful influences on people (Thaler and Sunstein, 2008). Others use the Nudge theory to explore, understand and explain existing influences on how people behave. The Nudge theory avoids direct instruction and enforcement by applying indirect encouragement and enablement. For example, in the context of WEF nexus, instead of building new institutions for implementing the nexus, its principles could be incorporated in existing (currently used) systems and institutions for easy adoption. The strength of the Nudge theory lies in accepting that people have attitudes, knowledge and capacities built from them. People are generally afraid of change; sometimes, too many changes that come with adopting the technology could be the very reason they reject the technology (Arno and Thoma, 2016). By Nudging "light touch or push", one could eliminate the fear of change.

Application of the nudge theory in scaling a technology could result in the loss of quality in technologies were maintaining the quality is important (Anderson, 2010). The Nudge theory could be more

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[3] The reader might want to reminisce on the trickle-down economic policies of the president Ronald Reagan administration in the USA in the 1980s!

appreciated for scaling specific principles of an approach rather than full scaling a technology as a whole.

8.5.6 Pathways to Impact Approach (PIA)

Public research needs to impact (use of research findings to change or benefit society or the economy). This impact is two-fold: policy intervention's impact and the generation of real-world impact from public research (Pherali and Lewis, 2019). Pathways to Impact Approach (PTIA) aims to guide the process of moving from research to impact or what others refer to as bridging the research-policy gaps (Hughes and Kitson, 2012; Jones and Bice, 2021). The steps outlined in the Pathway to Impact diagram (See Figure 8.3) are required to successfully implement the research-driven intervention.

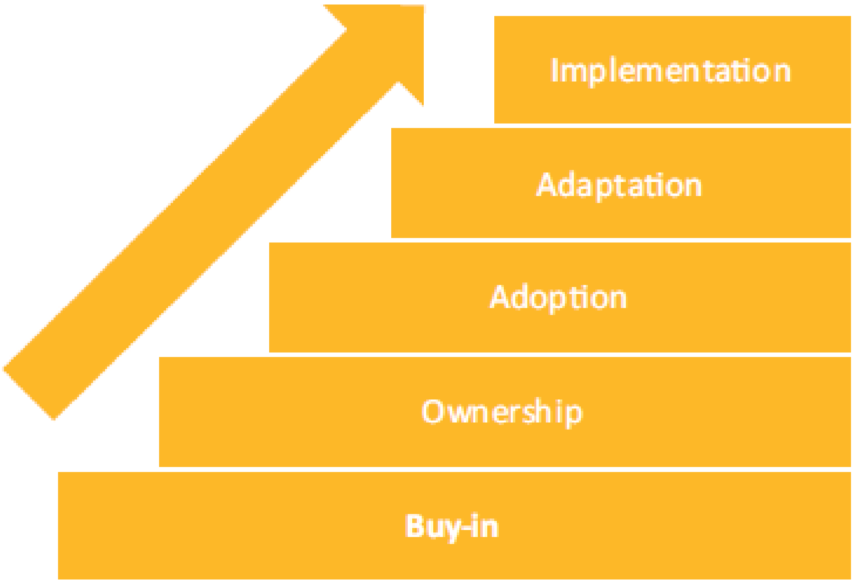

Figure 8.3 Pathway to impact step diagram (adapted from Jones and Bice, 2021)

Pathway to impact approach can be used to describe the process of identifying new partners. This is done through attending relevant events, working with external engagement teams or internal Knowledge Exchange (KE), and scoping meetings. The pathways to moving from research to impact are commonly long and frequently challenging. Jones and Bice (2021) argued long and confusing pathways could be tackled by planning the pathways from the initial stages of the project.

The building blocks of Pathway to Impact (See Figure 8.3) are critical for scaling out an innovation, technology or practice. The benefits of the technology or practice can diffuse to a larger population through the partnerships formed in the pathway to impact the process.

8.5.7 Soft Systems Methodology (SSM)

Soft System Methodology (SSM) is an action research method used to investigate real-world complex systems (Mehregan et al., 2012) and thus could potentially be applied to operationalise the WEF nexus.

It has been applied in numerous real-world problems, which include institutions of high learning timetabling system (Mehregan et al., 2012), reconstruction of education policy (Soemartono, 2014) and safety performance evaluation (Sgourou et al., 2012). This method allows the analyst, researcher, and participants to understand the problem from different perspectives (Mehregan et al., 2012). It consists of seven stages (see Figure 8.4), which are made of both real-world activities (Stages 1, 2, 5, 6 and 7) and thinking activities (Stages 3 and 4) (Nidumolu et al., 2006). In the following elaboration, to contextualise the discussion, one is encouraged to think of the problem as the need to operationalise the WEF nexus practice.

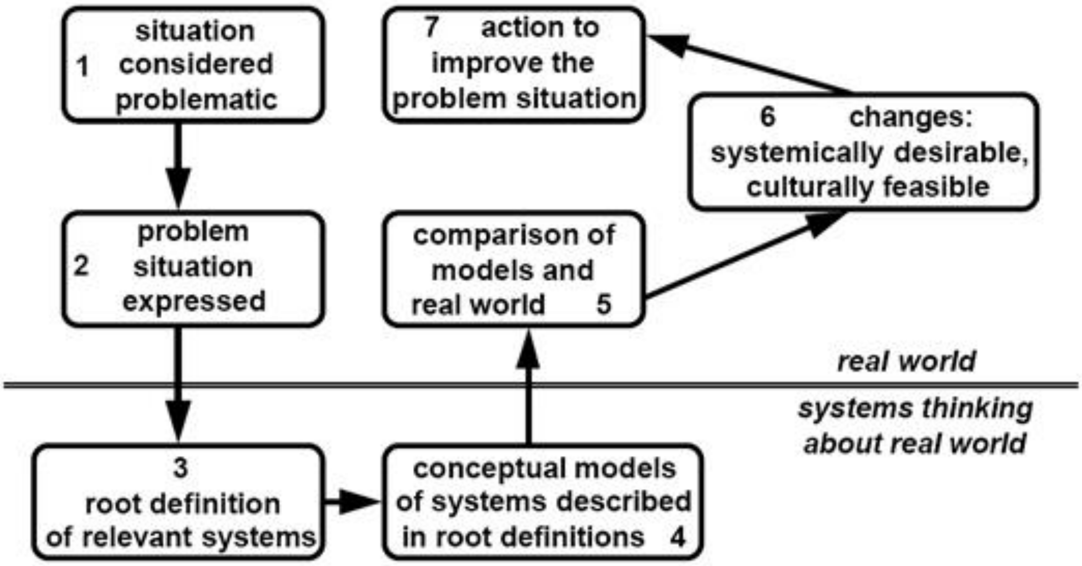

Figure 8.4 Seven stages of Soft System Methodology (SSM) (adopted from Nidumolu et al., 2006)

Stage 1 and 2: Identification and expression of the problem on the ground

Stage 1 and 2 of the SSM are undertaken concurrently. They aim to identify and express the real-world problem situation on the ground (Nidumolu et al., 2006). In Stage 1, stakeholders (involved in the structure of the problem) with different backgrounds are engaged in an interactive consultation process to identify the ground problem. Information about the problem is usually gathered using audio recorders, video recorders, short notes and open or close-ended questionnaires (Sgourou et al., 2012). The problems identified in Stage 1 are then expressed in a "rich picture" in Stage 2. Nidumolu et al. (2006) defined a rich picture as a diagrammatic representation of the problem at hand, which assists in identifying areas of interest in the problem situation.

Stage 3: Development of root definition

Here a Root Definition (RD) is derived from the rich picture developed in Stages 1 and 2. An RD is a single sentence statement of purpose that attempts to capture the essence of a specific situation in the whole problem situation (Niu et al., 2011; Mehregan et al., 2012). It provides a clear picture of what situation is being dealt with, and all components of the problem are considered. The mnemonic can best describe RD, CATWOE (Checkland, 1981), where C represents the Client (anyone who benefits from the output of the system), A represents the Actor (organizations that are part of the system and perform its functions), T represents the Transformations (the purpose not achieved into purposes achieved), W represents the Worldview (the viewpoint from which the system is being considered), O represents the Owner (an overall system decision-maker with concerns for the performance of the system), and E represents the Environmental constraints (those things outside the system which may have a significant influence on the system).

Stage 4: Development of a conceptual model

Based on a specific Root Definition, a conceptual model is derived using logic to determine the activities and their relationship, which needs to be in place to achieve the purpose described in the RD.

Stage 5: Comparison with Stage 4

The conceptual model is compared with the problem expressed in a rich picture in Stage 2. In the comparison, recommendations are made as to what needs to be done to ensure that the desired purpose is achieved. At this stage, the commonly asked questions are, "if what is appearing in the conceptual model, is it done in the real world and secondly, if it is done, how does or would it behave?" Based on the answers to the above questions, the recommendations are made.

Stage 6: Definition of desirable changes

At this stage, changes that need to be made to ensure the desired purpose is achieved are defined. These changes form an important part of the final model development.

Stage 7: Action to solve the problem situation

At this stage, further consultation with the stakeholders is undertaken to establish the action that needs to be taken to solve the problems at hand.

A consultative stakeholder engagement in Stages 1 and 7 of the SMM is essential for scaling up technologies and practices. Co-generation of information by involved stakeholders contributes to buy-in and enable easy sharing of ideas. This also creates a sense of ownership for the problem at hand, and accountability for tackling the problem could emerge. However, there is a risk of information not diffusing to reach stakeholders not involved in the process. This methodology is more effective in a face-to-face setting with the stakeholders. This limits its application to smaller geographical areas (e.g.

smallholder farming communities, villages level or municipal level), where travel to a central location would be easier.

8.6 Analysis of the Requirements for Upscaling and Outscaling of the WEF Nexus in South Africa

An analysis of the requirements for the upscaling and outscaling of the WEF nexus must, of necessity, start with a clear understanding of the challenges attendant with the various scaling approaches or types. Thereafter, one then has to contextualise this scaling in space and time.

8.6.1 Expectations, challenges and recommendations for various types of scaling

The question remains why there has not been any widespread adoption or uptake (i.e. up-scaling and out-scaling) of the WEF nexus, for example, in the SADC region. The region still faces numerous challenges to fully operationalise the WEF nexus as a conceptual framework and a discourse. Several factors (technical, political and social) delay the adoption and application of the WEF nexus. Barriers to up-scaling the WEF nexus approach have been widely studied. Some of these factors include the following for the SADC region (Mabhaudhi et al., 2020).

- *National vs regional aspirations*: There is little movement to show WEF nexus implementation as the focus is at the national or basin/regional levels. Although projections point to a stronger regional WEF integration, current progress is hindered by policy sections that allow countries to retain the right to develop and implement their national plans without being obliged to conform to the regional master plan (Nhamo et al., 2018). For instance, some Member States are delaying rectifying protocols on shared watercourses, as they do not envisage the need at the moment. At the national level, political sovereignty is still strong, which affects genuine cooperation and integration. Regional cooperation in development programmes does not remove national sovereignty but fosters integrated economic development and poverty alleviation. Despite this, there is little evidence of commitment by the Member States to implement the WEF nexus at a regional level. While the national focus may have positives, the shared nature of resources suggests that pulled investments may achieve a greater impact at a regional rather than national scale. Regional countries may also have limited resources to engage and implement the WEF nexus when they might be having more pressing issues such as security consideration, stability and internal displacement of populations.
- *Political will*: Despite a belief in the WEF nexus as a resource management tool; there could be low buy-in from member country politicians and technocrats. This is not surprising given that some member countries are yet to sign regional protocols on shared resources (Nhamo et al., 2018). Fatigue by member states to have to kowtow to ever-changing and shifting developmental paradigms; not so long ago, it was IWRM, but now it is WEF nexus.

- *Funding*. Dependency on donor funding to implement the WEF nexus could be another limitation, given that donor funding always comes with operational complexities.
- *Availability of expertise*: From a technical perspective, it could also be that there is limited technical expertise in the region on the WEF nexus.
- *Data availability*: Lastly, problems associated with data and tools could be a limitation. Most of the tools and models for undertaking WEF nexus analyses were developed in Europe and America's resources and data-rich northern countries. The same cannot readily be said for the SADC region.

Studies have made recommendations on how such barriers can be tackled. The recommendations provide the first step towards determining the requirements for up-scaling and out-scaling the WEF nexus approach. The table below (Table 8.4) summarises challenges encountered with various types of scaling and the proposed or suggested recommendations for scaling.

Table 8.4 Expectations, challenges and recommendations for various types of scaling.

Type of scaling	Expectations	Challenges	Recommendation or requirement for scaling the nexus approach
Out-scaling	• Awareness-raising is important for scaling a technology • Competition with other/ existing technology option (a technology need to be better than existing technology options • Knowledge of what works, in which contexts is sometimes a prerequisite to scaling technology or practice • Elements of the technology/practice to be scaled needs to be determined before planning to scale technology or a practice • Who is going to drive the scaling of the WEF nexus approach?	• Most of the WEF nexus workshops aimed at raising awareness of the WEF nexus and its potential benefit were held at an international, regional and national level, with fewer or no awareness-raising workshops at a local level • The WEF nexus is at its infant stage of implementation (not much testing has been carried out) • The is no single WEF nexus solution (most nexus solutions are context-specific) which makes it harder to scale up • There is still a debate in the literature about who owns the WEF nexus?	• More focus on a practical case study of the application of the WEF nexus, especially at the local level. • More pilot studies on WEF nexus solutions are needed, and documentation of scalable WEF nexus solutions is needed • Identification of key players for scaling the nexus is needed
Up-scaling	• Dialogue at different levels (regional, national, provincial and local scale) • Political buy-in is required • Changing policies, laws, rules and regulations	• These dialogues need to be supported by scientific evidence (however, data, analytical tools, and models to support the generation of scientific evidence are still lacking) • Bridging the science-policy gap remains a challenge • Stakeholders representation in the WEF nexus dialogues from government/ policymakers are often experts with no influence to changes that affect policy	• Making available the resource to general the scientific evidence to support the dialogues • Involvement of stakeholders with influence or powers to change of affect policy
Deep scaling	• Changing stakeholders mindsets • Changing stakeholders cultural values and practices • Changing stakeholders beliefs and value systems	• Stakeholders resistance to change and lack of buy-in • Lack of non-committal to changes of any kind and type • Strongly imbued beliefs and value systems that are unlikely to change	• Enhancement of knowledge about the WEF nexus • Change in attitudes toward the WEF nexus • Change in practices linked to the WEF nexus • Complete buy-in to the WEF nexus through training and dialogue

The entry point to solving the problem of up-scaling and out-scaling the WEF nexus is fully appreciated the requirements for this to happen, i.e. what needs to be in place for the WEF nexus to be up-scaled and out-scaled? Once this is determined, the next step would be to assess if these requirements exist or are in place and properly aligned. In cases where the requirements are not in place and properly aligned, the next step would be to create or develop these missing desirable conditions and requirements. Obviously, this is easier said than done, but it's a start and almost a sure way to succeed in the up-scaling and out-scaling of the WEF nexus. In the following sections, an attempt is made to define and itemise the requirements for scaling the WEF nexus. This will be summarised for the different up-scaling and out-scaling methodologies presented in this report (see Table 8.5).

8.6.2 Contextualising upscaling and outscaling in space and time

The WEF nexus up-scaling and out-scaling would need to be contextualised in space and in time. This contextualisation is imperative if success is to be made of the scaling of the WEF nexus. The spatial scale requirements differ from the temporal requirements, and a combination of space and time produces the final picture of the whole process.

Spatial scale is crucial in the up-scaling and out-scaling any innovation or practice, including the WEF nexus. A lot of the requirements are scale-dependent, and consequently, the scale must be defined and categorised. Scale and innovation mismatches can result in unintended consequences (Sandel and Smith, 2009) in other parts of the system. The spatial scale for the WEF nexus can be categorised into (lower to higher levels); local, district or municipality, provincial, national and regional. Depending on the country, there might be some (slight) variations to these spatial scales. For example, one could have the WEF nexus being applied in a given locality, e.g. a sub-catchment and then moving to the next set of sub-catchments and finally the whole catchment before being out-scaled to other catchments. Apart from the time requirements for this to occur, there needs to exist conditions amenable to the uptake of the WEF nexus at all these spatial scales.

Concerning the temporal scales, these can be simplified to the following three categories; immediate (e.g. up to 12 months), medium-term (up to 24 months) and long term (up to 36 months and beyond). This temporal scaling can be highly variable depending on what is trying to be achieved. For example, let's assume a national government wants to adopt the WEF nexus approach for natural resources management; the process would, of necessity, have to start with the national planning office and the relevant ministry adopting and embedding the WEF nexus approach, then this has to devolve down to the provincial governments, next down to the district or municipalities and finally down to the local level. There might be a need to reorganise government structures, train staff, and marshal requisite resources, among other requirements. Even under the best of circumstances, such a process cannot be accomplished within a year, most likely over a 3 to 5-year time horizon. Under these conditions, the requirement for successful up-scaling of the WEF nexus would be 36 to 60 months and no less. The time investment into up-scaling and out-scaling any practice or innovation cannot be downplayed; it's crucial. As an equivalent example, the concept of integrated water resources management (IWRM) started over 20 years ago, yet there is no wholesale acceptance, adoption and practice of IWRM worldwide.

Another important issue is the aspect of measures of success and failure to the up-scaling and out-scaling efforts. Simply put, the question is what needs to be in place or to have been achieved for us to say the up-scaling and out-scaling WEF nexus has been a success? Examples of success vary from simply quantifying the number of units or departments or countries that would be applying the WEF nexus to much more robust measures, such as cases or situations of optimally managed (maximised synergies and minimised trade-offs) natural resources cases over given time scales. It is important to always attach a time aspect to assessing the success or failure of the adoption of innovation or practice because, more often than not, in the short term, adoption rates tend to be high (success?) and then drop off precipitously (failure?) a few years down the line.

The following sub-sections discuss the various spatial scales involved in the up-scaling and out-scaling of the WEF nexus and a brief qualitative assessment of the key requirements for the successful up-scaling and out-scaling. The scale categorisations are complicated by the need to distinguish whether these are administrative or geographical boundaries. Often, geographical boundaries traverse or cross administrative boundaries, and therein lies a further complication. Where possible, the time scale will be juxtaposed to the spatial scale requirements.

The key requirements to the up-scaling and out-scaling of the WEF nexus will be categorised under; technical, institutional, socio-economics and physical factors. Technical factors will include; expertise, data, and technologies (soft & hard). Institutional factors will include; governance structures, laws, regulations and policies, governance processes, and power and people. Socio-economic factors would include; roles and responsibilities of individuals and structural units, peoples resources endowment, livelihood strategies and related alternatives and incomes. Lastly, physical factors would include; land, water and energy resources, ecosystem goods and services and infrastructure.

Local scale

The local scale is probably the smallest or lowest unit one can go up-scaling and out-scaling the WEF nexus. In South Africa, administratively, the local scale would include; families are deriving livelihoods from land, water and energy resources, smallholder communal farmers and small-scale commercial farmers (both irrigated and rainfed agricultural practices), communal set up under a kraal head or similar arrangement. Geographically, the local scale could be equated or likened to sub-sub-catchment and sub-catchment. The boundaries would be different in an urban setting, hence the water, energy, and food security dynamics.

The local scale is characterised by resources, goods and services moving in and out across its boundaries. Concerning WEF nexus, resources, except land, water, energy, and food, move across the boundaries, and the balance could be severely skewed to the inward flow of such goods and services.

There is generally a lack of technical resources concerning the requirements for up-scaling and out-scaling the WEF nexus at the local scale. Such populations are dependent on government or non-governmental technical expertise when it's available. Similarly, institutional setups at the local scale tend to be basic and self-serving, depending mainly on cultural practices and less on formalised laws, rules and regulations. The socio-economics at the local scale are also mainly rudimentary and depend on local practices, incomes and livelihood strategies can be severely constrained by the availability of resources and opportunities and high unemployment levels. On the physical factors, typical these are limited as seen in limited land holding sizes, at times as low as 0.1 ha per family in irrigated agriculture, no secure tenure to land, limited water resources, no water permit for productive water use, and no clean energy due to the use of firewood as a source of energy.

Consequently, the prospects of up-scaling and out-scaling the WEF nexus at the local scale are low and limited unless the practice is homegrown or supported from the top with substantial government input and handholding. The irony of the situation is that the smallholder rural dweller would benefit the most if the WEF nexus were implemented at this scale.

District/Municipal scale

Municipalities in South Africa come in three categories: metropolitan municipalities (for the large metropolitan areas) and district municipalities, and each of these districts comprises local municipalities. Currently, there are eight metropolitan municipalities, 44 district municipalities and 205 local municipalities. The eight metropolitan municipalities act as both district and local municipalities. Administratively, districts are the second level of administrative division, falling below the provinces and seating (in the case of district municipalities) above the local municipalities. Currently, South Africa has 52 districts, and each district is now completely contained within a single province, thus eliminating cross-border districts and the related administrative problems.

The districts are particularly interested in the up-scaling and out-scaling of the WEF nexus because South Africa has adopted the so-called District Development Model (DDM). The DDM consists of a process by which all three spheres of governance undertake joint and collaborative planning at local, district and metropolitan levels, resulting in a single strategically focussed "One Plan" for each of the 44 districts and eight metropolitan geographic spaces in the country. The DDM seeks to ensure that "the local government is capacitated and transformed to play a developmental role" through having "a local government committed to working with citizens and groups within the community to find sustainable ways to meet their social, economic and material needs and improve the quality of their lives".

In summary, and relating to the WEF nexus, the objectives of the DDM are (https://www.cogta.gov.za/ddm/):

- Coordinate a government response to challenges of poverty, unemployment and inequality, particularly amongst women, youth and people living with disabilities.
- Ensure inclusivity by gender budgeting based on the needs and aspirations of our people and communities at a local level.
- Narrow the distance between people and government by strengthening the coordination role and capacities at the District and City levels.
- Foster a practical intergovernmental relations mechanism to plan, budget, and implement jointly to provide a coherent government for the people in the Republic; (solve silo's, duplication and fragmentation) maximise impact and align plans and resources at our disposal through the development of "One District, One Plan and One Budget".
- Build government capacity to support municipalities.
- Strengthen monitoring and evaluation at district and local levels.
- Implement a balanced approach towards development between urban and rural areas.
- Exercise oversight over budgets and projects in an accountable and transparent manner.

In theory, it would follow that the requirements for up-scaling and out-scaling the WEF nexus would be availed and met at the district and municipality levels because these are the foci of integrated development across the nation. Through the DDM, the districts and municipalities are strongly recommended to be used as entry points to the up-scaling and out-scaling of the WEF nexus in South Africa. At this scale, technical, institutional, socio-economic and physical requirement factors for the up-scaling and out-scaling of the WEF nexus can be available and met.

Provincial scale

South Africa is administratively divided into nine provinces; each has its legislature, premier and executive council. The provinces are; Eastern Cape, Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape and North West. The provinces are diverse in everything. The characteristics of the provinces have previously been discussed concerning the WEF nexus (see Deliverable 3 and WRC Report No KV 365/18). Suffice to say that Northern Cape has the largest land area, the eastern seaboard provinces (KZN and Mpumalanga) get the most rainfall, Gauteng is the economic engine of the country and has the highest population, agriculture is the backbone of

Mpumalanga, and Western Cape produces a wide variety of wines, and 75% of South Africa fishing is from this province.

The provinces have all the governance structures and receive budget allocations from the national government to run all their affairs. The provincial government is run by an Executive Council (ExCo), consisting of the premier and five to ten Members of the Executive Council (MEC). The premier designates the powers and functions of the MECs, and they are conventionally assigned portfolios in specific areas of responsibility, e.g. agriculture, education, health and so on. The MECs are accountable to the provincial legislature and regularly report to the legislature on the performance of their specific responsibilities and portfolios.

Concerning the up-scaling and out-scaling of the WEF nexus at the provincial scale, all the requirements are generally present and can be availed. The provinces are formally well-equipped as they have governance structures, policies, rules and regulations, governance processes, power and manpower. Similarly, technically, they have the expertise or can sub-contract expertise, technologies, and access to key data for decision making. On the socio-economic front, the provinces have a budget that covers most of the activities of the various portfolios under the respective MECs, and the roles and responsibilities are clear. Concerning physical factors, the provinces generally, except for Gauteng maybe, have land resources, infrastructure, ecosystems good and services and water and energy to some extent depending on the specific province.

The provinces, working together with the municipalities and districts through the DDM, are ideal places for up-scaling and out-scaling the WEF nexus.

National scale

The government comprises three inter-connected branches; the legislature, the executive, and the judiciary. South Africa's governance is unique. The national, provincial and local levels of government all have legislative and executive authority in their spheres of operation, and are taken as distinctive, interdependent and interrelated.

Concerning the WEF nexus, at the national level, the relevant departments are the Department of Water and Sanitation (DWS), Department of Agriculture, Land Reform and Rural Development (DALRRD), which cover land and food production, Department of Public Enterprises (DPE) under which the power (energy) entity Eskom is governed, and Department of Social Development (DSD) dealing with livelihoods aspects. These departments' roles in the WEF nexus dynamics have previously been discussed (WRC Report No KV 365/18). A department worth mentioning is the Department of Planning, Monitoring and Evaluation (DPME), whose mandate includes facilitating, influencing, and supporting effective planning, monitoring and evaluation of government programmes to improve service delivery, outcomes, and society's impact. At times, it has been hinted that the DPME be the custodian of the WEF nexus in South Africa.

The national is responsible for working out budgets and plans for national development. It follows that, if and when needed, all the requirements for up-scaling and out-scaling the WEF nexus can be planned for and made available as the institutional, technical and economic structures are in place. If it’s a top-down approach, the WEF nexus planning approach can be initiated at the national level and then cascaded down to the provinces and the municipalities and districts.

Provincial scale

The regional scale could comprise countries in the southern Africa region or SADC, or even sub-Saharan Africa. GWP-SA is coordinating efforts in that direction for the SADC region, which will not be discussed further here.

Table 8.5: Summary of the key requirements for up-scaling and out-scaling of the WEF nexus for the different approaches

Approach	Definition (what it is)	Applicability Technology or Innovation or Practice or Tool	Applicability Scale (local, district, municipality, provincial, national)	Applicability (up-scaling, out-scaling, deep-scaling)	Steps or Process (Key steps or processes)	The Requirements (socio-econo-technical)	Timelines (months) (slow 36, moderate 24, quick 12)	Cost (low moderate, high)	Flexibility or Adaptability (yes, so so, no)
Communications Pathway Approach	A process that is based on developing a message, then sending it through a channel or pathway to the target receiver (and allowing for feedback)	Technology, practice and tools	Local, district, municipality, provincial, and National levels	Up-scaling and out-scaling	• What is the product • Who are the stakeholders • Communication plan & pathway • Packaging the product • Communicating the product • M&E the communication and uptake • Improve & iterate	• Message packaging • Communication pathway • Ready receiver	Quick to moderate 12 to 24 months	Low to moderate	Adaptable and flexible
Diffusion of Innovations Approach	A process that enables new products to be adopted or rejected by their intended audiences. It portrays the speed and pattern at which new practices spread through a population.	Practice	Local, district, municipality, provincial, and national	Out scaling	• Knowledge – Characteristic of the decision-making unit. • Persuasion – Perceived characteristics of innovation (relative advantage, compatibility, complexity, trialability and observability) • Decision – Adoption or rejection • Implementation • Confirmation	• Socio-economic characteristics • Personality variables • Communicative behaviour	Moderate 24 Months	Low cost	It is flexible and adaptable. It can fit informal and formal environments during adoption.
Trickle-down or Trickle-up Approach	A process that is based on the assumption that if you train or capacitate people at the top or higher up in a system, the	Technology or innovation or practice	National to local scales	Mainly up-scaling	• Identify the message or innovation • Train or capacitate those at the higher level • Wait for the knowledge or innovation to cascade to the lower levels	• The message or innovation • Training of those at the higher levels • Message or practice trickles down	Moderate to slow (24 months and beyond)	Low to moderate	Tend to be slow and not a managed trickling down

Approach	Definition (what it is)	Applicability Technology or Innovation or Practice or Tool	Applicability Scale (local, district, municipality, provincial, national)	Applicability (up-scaling, out-scaling, deep-scaling)	Steps or Process (Key steps or processes)	The Requirements (socio-econo-technical)	Timelines (months) (slow 36, moderate 24, quick 12)	Cost (low moderate, high)	Flexibility or Adaptability (yes, so so, no)
	knowledge and practices will trickle down to the lower levels					to a lower level			
Nudge Theory	A process that is based on indirect suggestions as well as gentle persuasion and positive reinforcement to change peoples' behaviour, in this case taking up a new practice or innovation	Practice	Local-scale	Out-scaling	• Identify the practice • Identify the target beneficiary • Apply positive reinforcement • Wait for behavioural change	• Clear message • Target beneficiary • Interlocutor applying positive reinforceme nt • Time for a change to occur	Slow	Low	Adaptable to various practices
Pathways to Impact Approach	A process of identifying the required impact or outcome right from the start and planning the pathway to get to the outcome, in this case, adopting new technology or practice	Innovation or technology	Local to national	Up-scaling and out-scaling	• Identify the innovation or technology • Plan the pathway • Implement the message through the pathway • Monitor and evaluate to ensure impact	• The message • Clear pathway • Ways and means to enforce message through a pathway • Monitoring and evaluation capability	Quick to moderate	Medium to high	Adaptable to existing situations and resource base
Theory of Change	An approach for planning, participation, and evaluation	Practice or innovation	Local to national	Up-scaling and out-scaling	• Identify or develop the practice or innovation	• The message • A plan • How to implement	Moderate to slow	Moderate to high	Adaptable if there is time

Approach	Definition (what it is)	Applicability Technology or Innovation or Practice or Tool	Applicability Scale (local, district, municipality, provincial, national)	Applicability (up-scaling, out-scaling, deep-scaling)	Steps or Process (Key steps or processes)	The Requirements (socio-econo-technical)	Timelines (months) (slow 36, moderate 24, quick 12)	Cost (low moderate, high)	Flexibility or Adaptability (yes, so so, no)
	promotes change, i.e. adopting new technology or innovation.				• Plan and create conditions on how to implement the new practice • Implement • Monitor and evaluate	• Monitoring and evaluation			

8.7 Housing of the WEF Nexus Operationalisation Mandate in South Africa

The issue of housing the operationalising of the WEF nexus was covered in Section 8.6.2. In short, a department worth mentioning is the Department of Planning, Monitoring and Evaluation (DPME), whose mandate includes facilitating, influencing, and supporting effective planning, monitoring and evaluation of government programmes to improve service delivery, outcomes, and society's impact. It is suggested or proposed that the DPME be the custodian of the WEF nexus in South Africa.

8.8 Concluding Remarks

Generally, socio-economic development is driven by key strategic resources: water, energy, food, and land. Unfortunately, and regrettably, these strategic resources are degrading and over-exploited due to pollution, climate change, population growth, economic development, changing diets, urbanization, cultural and technological changes (Mabhaudhi et al., 2016a). The near future projections for 2030 predict demand increases of 40% for water and 50% for energy and food. Furthermore, the resources of water, energy and food (WEF) are interconnected, meaning that a change in one will impact the other two. Water, energy and food securities are inextricably linked, with usage within one sector influencing the use and availability in the adjacent sectors. It is against this background that the WEF nexus emerged. The WEF nexus is generally defined as an approach that considers the interactions, synergies and trade-offs of water, energy and food when managing these resources.

The WEF nexus has been contextualised and applied as a concept, a conceptual framework, analytical framework, a discourse, a tool, innovation and even as practice. These many 'faces' of the WEF nexus are because of its adaptability and practical relevance. However, the WEF nexus is considered a tool that is applied in managing natural resources such as water, land and energy to ensure sustainable development. As an analytical tool, the WEF nexus systematically applies quantitative and qualitative methods to understand the interactions among WEF resources. At the United Nations level, the WEF nexus has been adopted as a vehicle that can be used to attain some of the sustainable development goals (SDGs), especially SDGs 2, 6 and 7, since it is closely related aligned to the SDGs.

The main challenge and disappointment to date is the low uptake or mainstreaming of the WEF nexus as a planning tool in many places, including South Africa. As already discussed in this report, several important factors militate against the uptake or adoption of the WEF nexus.

The SADC region, including South Africa, resolved and agreed to apply the WEF nexus as a tool for natural resources management. It is thus imperative that the scaling of the WEF nexus be fully understood and be prepared for.

Scale issues, both in space and time, are important in adopting and potential application of the WEF Nexus. The spatial scale ranges from local to regional. In a country like South Africa, the administrative spatial scales would cover local, district, municipality, provincial and national scales, and then regional if one considered the SADC region. The WEF nexus is indeed applicable at all these spatial scales, although the dynamics vary somewhat.

For the temporal scale, the WEF nexus implementation can be applied in the short term, medium-term, and long term, like other innovations or technologies. There are no hard and fast definitions of these time scales, but as a working example, the short term could be up to 12 months, medium-term up to 36 months and long term more than 36 months. The temporal scale goes together with the spatial scale. For example, applying the WEF nexus to the local scale would probably take much shorter than applying it at the national scale.

Generally speaking, scaling refers to the process of increasing the number of people or beneficiaries or stakeholders benefiting from a technology or practice or innovation. In the main, scaling can be vertical (up-scaling) or horizontal (out-scaling), but can also be considered in other forms. Unfortunately, technologies, innovations or practices are not automatically scalable – some are easy to scale than others. Furthermore, not all aspects or components of a technology or innovation are scalable. Usually, scaling is considered if and when there is perceived potential that the technology or practice would benefit a wider population.

Up-scaling talks about impacting laws and policies, thus changing institutions at the policy, laws and rules level. Out-scaling talks about impacting a greater number of beneficiaries or people, meaning replication and dissemination and increasing the number of people or beneficiaries impacted. Lastly, deep scaling talks about impacting cultural roots, thus changing beliefs, cultural values and working relationships.

The WEF nexus as a tool is no different from other technologies or innovations regarding scaling issues. For the successful scaling of the WEF nexus, it is important that the requirements for scaling are fully understood and conditions created for these requirements to be met or to exist.The requirements to the up-scaling, out-scaling and deep scaling of the WEF nexus can be categorised under; technical, institutional, socio-economics and physical factors. Technical factors include; expertise, data, and technologies (soft & hard). Institutional factors include; governance structures, laws, regulations and policies, governance processes, and power and people. Socio-economic factors would include; roles and responsibilities of individuals and structural units, peoples resources endowment, livelihood strategies and related alternatives and incomes. Lastly, physical factors include; land, water and energy resources, ecosystem goods and services and infrastructure.

9 CHAPTER 9: ASSESSMENT OF THE IMPACTS OF CLIMATE CHANGE ON THE WEF NEXUS IN SOUTH AFRICA

9.1 Introduction

South Africa is a contributor to, and experiences the consequences of, global Climate Change (CC) (Herrfahrdt-Pähle, 2010). With a Mean Annual Precipitation (MAP) of 500 mm (GoZa, 2015; Makou, 2017), South Africa is classified as a water-stressed region, and through evaporation losses and projected increased fluctuations in rainfall, the overall surface water available in South Africa is expected to decrease (Mpandeli et al., 2018).

CC impacts on Surface Water Availability (SWA) vary for each catchment area in South Africa (Knight, 2016). This is apparent from the various projections of mean annual runoff (MAR) through South African catchments. By 2050: (a) Warburton (2012) projected MAR to decrease by up to 35% for Upper Breede catchment in Cape Town, (b) for the uThukela catchment in KwaZulu-Natal, CC scenarios projected a 16% to 38% increase in MAR (Graham et al., 2011), and (c) in the Upper Crocodile River catchment in Johannesburg, MAR is projected to decrease by 39% (Leketa and Abiye, 2019). SWA variations affect the ecological environment and the socioeconomic system of catchment communities (Herrfahrdt-Pähle, 2010).

Power generation uses a significant amount of water obtained from catchment Water Transfer Schemes (WTS); South Africa's state-owned electricity utility, Eskom, receives its water supply comes from: (a) Komati WTS in the Komati River catchment, (b) Usutu and Usutu-Vaal Government WTS, and (c) Zaaihoek WTS in the Buffalo River (BR) catchment (Eskom, 2018). By 2030, Eskom's water consumption per annum is expected to be 270 billion litres (Buthelezi, 2012). Irrigation produces 90% of South Africa's high-value crops. However, it consumes 62.6% of the total water available (Donnenfeld et al., 2018; Van Niekerk et al., 2018). Given the pressures imposed by CC on SWA and the fact that water supply has already been completely or over-allocated in many of South Africa's catchments (VanNiekerk et al., 2018), CC assessments and adaptation strategies, therefore, require cross-sectoral approaches to promote efficient use of resources and sustainable development of the water, energy, and food sectors (Mpandeli et al., 2018).

9.2 Climate Change and Climate Variability Dynamics and the WEF nexus

9.2.1 Climate change impacts on water resources

CC is expected to increase runoff along the eastern seaboard and in South Africa's central interior as a result of anticipated increases in precipitation. However, in the Western Cape, declining runoff is projected due to decreased rainfall and drying (DEA, 2013a). Rainfall in the Breede River catchment, the largest river in the Western Cape and a vital resource for many economic activities there, is anticipated to decline by 2080, resulting in MAR that will be less than the ecological water requirements (Steynor et al., 2009).

The Eastern Cape, southern Mpumalanga, and KZN are among the regions with the highest probabilities of severe runoff-related occurrences (DEA, 2013a). In KZN, streamflow projections in the Umgeni River catchment depicted an increase of up to 2.6 and even 5.3-fold by 2065 and 2100, respectively, and high risks of extreme peak streamflow are expected in the Nagle, Lions and Mpendle catchments (Summerton and Schulze, 2009). Similarly, based on ten regionally downscaled future climate projections, Graham et al. (2011) projected a substantial 16% to 38% increase in the Thukela River runoff by 2100. However, Graham et al. (2011) further stressed the likelihood of runoff decreases in the Thukela River; one of the downscaled projections showed a decrease in runoff in the mid- and distant-future. Emphasis was therefore made to include different perspectives in runoff in water security management. Other catchments show neutral to reduced risk in runoff (DEA, 2013a).

9.2.2 Impacts of climate change on the agricultural production sector

The overall Irrigation Water Requirements (IWR) in South Africa represent 62.6% of the total water use per sector (Donnenfeld et al., 2018). During the period 2002 to 2013, the area under irrigation has increased from approximately 0.77 million ha to 1.3 million ha (Baleta and Pegram, 2014), producing about 30% of the country's crops, hence making it essential for optimal production of agricultural products (DEA, 2013b). Less than 800 mm in the eastern and southern areas and more than 1600 mm in the north-western regions constitute the mean annual net IWR over South Africa (Schulze and Taylor, 2016). Intermediate (mid-future) projections show a 10% decrease of IWR in the central and eastern regions of South Africa due to increased rainfall outweighing increased demands triggered by higher temperatures and increased evaporation. In the drier western half and northern quarter of the country, IWR is expected to increase by 10% as depicted by Figure 9.1. However, in the distant future, 90% of South Africa's irrigation demands are projected to increase by 10-20%, and parts of the south-western Cape by even greater than 20%, also seen in Figure 9.1 (Schulze and Kunz, 2010).

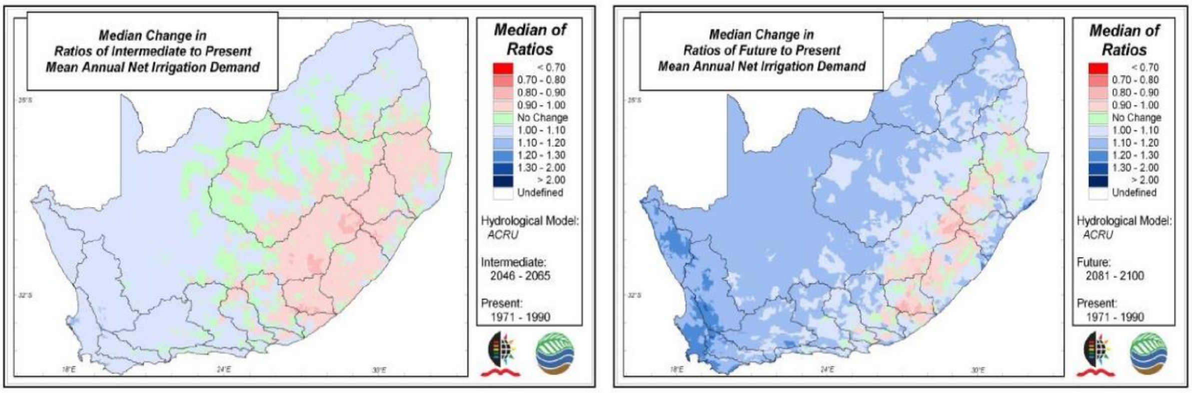

Figure 9.1 Median changes in ratios of intermediate (left) and future (right) to present net IWR, computed with the ACRU model from output of multiple GCMs (Schulze and Kunz, 2010)

The KZN province's agricultural development is extremely sensitive to CC (Shezi and Ngcoya, 2016). The effects of CC are projected to exacerbate food insecurity in the coastal and northern parts of KZN through increased temperatures and rainfall (Zwane and Montmasson-Clair, 2016). The coastal KZN eThekwini municipal areas will suffer from crop impairment due to increased temperatures. Low crop yields are expected as the anticipated rainstorms and floods will cause leaching of nutrients and water-logged soils (Shezi and Ngcoya, 2016). The same is to be expected for the Amajuba and uMzinyathi municipalities, located in northern KZN's BR catchment where increased temperatures, drought, and increased frequency and severity of storm flood events will also be the cause of crop impairment (DCGTA, 2015; LGCCP, 2018). Socio-economic instability in such catchment communities will therefore be worsened by this through increased food insecurity, and consequently aggravated poverty conditions, especially in communities that rely heavily on rain-fed agriculture (Ofoegbu et al., 2017).

9.2.3 The future for energy generation water demands

Coal makes up 67% of South Africa's primary energy source, with crude oil contributing 20%. The remaining 13% is composed of nuclear, natural gas, and renewable energy sources (such as hydropower and biomass). 91% of South Africa's electricity is generated from coal, and the majority of it is done so by Eskom's coal-fired power facilities (Goga and Pegram, 2014). These coal-fired plants substantially impact water as they use a significant amount of it throughout each electricity generation process, especially the cooling process, as seen in Table 9.1. Eskom consumes an estimated 334 Gigalitres of water annually (GL.yr-1) for power production, which is equivalent to 2% of South Africa's water supply (Sparks et al., 2014).

Table 9.1 Water usage in energy production by using thermal electric cycles (Sparks et al., 2014)

Fuel	**Energy Production Stage**	**Water Use (litres/MWh)**	**Sources**
Coal	Pre-generation, mining & washing	183-226	(Martin and Fischer, 2012)
	Generation, cooling	1 420	(ESKOM, 2013b)
	Generation, dry cooling	100	(ESKOM, 2013b)
	Generation, indirect dry cooling	80	(Martin and Fischer, 2012)
	Generation, cooling	1380	(Martin and Fischer, 2012)
Nuclear	Generation, cooling	192 539	(ESKOM, 2013a)

Ten baseload plants, three return-to-service (RTS), and two newly constructed power stations comprise the fleet of coal power plants in South Africa. According to Thopil and Pouris (2015), the RTS power plants use the most water, and by 2020, their water consumption factor was predicted to reach 3 litres/kWh. The total energy-water requirement was projected to drop by 12 to 15% if the RTS fleet retired by 2020 (~40 $GL.yr^{-1}$), as shown in Figure 9.2. If not, the water requirement was projected to roughly increase to 370 $GL.yr^{-1}$ by 2035 and beyond (Thopil and Pouris, 2015), which will weigh even more heavily on the water resources (Wassung, 2010). Currently, of the three water-consuming RTS power plants, the Komati has been retired (ESKOM, 2022). However, Eskom opted to postpone the retirement of the two remaining RTS power stations, Camden and Grootvlei, until 2030 (ESKOM, 2020), thus still posing a threat to water resources.

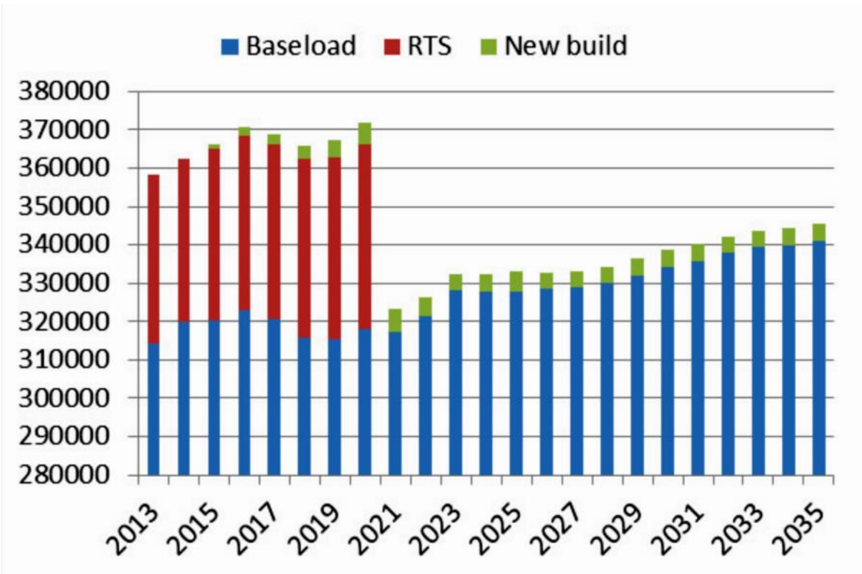

Figure 9.2 Combined water consumption (Megalitres per annum) of the baseload, RTS and new build power plants (*y-axis = Water consumption, *x-axis = year) (Thopil and Pouris, 2015)

The likelihood of energy generation requiring more water supply poses potential conflicts with the water and food sectors (Mpandeli et al., 2018), especially since Eskom receives its water supply through catchment water schemes that provide water to other users (Eskom, 2018). The Zaaihoek Water Transfer Scheme, which forms part of the BR catchment in northern KZN, transfers 12% of its water to the Majuba power station for cooling purposes. The rest gets supplied to Water Treatment Plants (WTPs) and irrigation within the BR catchment (uMgeni, 2020). The Zaaihoek dam has been deemed unsuitable for further water allocations (Dlamini and Mostert, 2019) , thus any increases in water demands for energy will cause consequential impacts on other water demands, triggering the destabilization of the catchment's health and socio-economic state. (Singh et al., 2018). Therefore, further energy generation water demands must be addressed in conjunction with the food and water demands. Management strategies for energy security should take into account trade-offs with the food and water sectors as well as the pressures of CC on these resources (Mpandeli et al., 2018).

9.3 The WEF Nexus as a Natural Resources Planning Tool under Climate Change

The Water-Energy-Food (WEF) nexus is a methodology that offers an in-depth comprehension and methodical analysis of the connections between the environment and human activities to achieve more integrated management and utilization of natural resources across sectors and scales (McNamara et al., 2018). WEF nexus assessments can be carried out using Conceptual Visualisation Tools (CVT) or Quantitative Analytical Tools (QAT), all of which constitute modelling tools. Frequently, modelling tools employ monthly time series data for parameters (e.g. climate, water and crop yields, agricultural areas and energy generation) to simulate determined target values based on various inputs (McNamara et al., 2018). The simple manner in which models represent and simulate processes serves their advantage (Parra et al., 2018). They can be used to assess a system's sensitive components and simulate future scenarios for decision support in planning (McNamara et al., 2018). For climate change and basin management, the use of water balance models has recently increased, especially in CC impact studies and for the simulation of different environmental processes (Parra et al., 2018).

9.4 Applicable Models and Tools

In South Africa, numerous models can be applied to carry out a WEF nexus assessment, as displayed in Table 9.2 (Mabhaudhi et al., 2018). Analytical models that deal specifically with WEF resources management and CC are the Climate, Land-Use, Energy and Water Strategies (CLEWS) and the ANEMI model. While the ANEMI model carries out an interconnected evaluation of the physical, ecological, and hydrological processes (Davies and Simonovic, 2010; Mabhaudhi et al., 2018), the CLEWS involves integrating detailed land, energy and water models under various climate scenarios, hence enabling flexibility of analytical model selection for each WEF component (Mabhaudhi et al., 2018).

Table 9.2 Tools and models applicable in South Africa for WEF nexus assessments (adopted from Mabhaudhi et al., 2018; Nhamo et al., 2020)

Nexus Tools	Modelling Framework	Scale	System Breadth	Analytical Capability	Flexibility	Applicability to WEF nexus in South Africa
Integrated Analytical Model	Calculating composite indices of defined WEF nexus indicators	All scales	WEF nexus components, socio-economy, environment	Indices provide an overview of the level of interactions, inter-relationships and inter-connectedness among water, energy and food sectors	Only considers indicators related to the security of water, energy and food resources	Yes
WEF Nexus Tool 2.0	Input-output	National	WEF nexus components	Scenario-based for given food self-sufficiency level calculates nexus resource flows and interactions, and greenhouse gas (GHG) emissions	Focused on food as an entry point and Qatar country	Yes
MuSIASEM	Input-output nested hierarchical view of the economy	Aggregated to national or sub-national level	WEF nexus components, land, economy, human capital and ecosystems	Accounting of flows and funds and their ratios as Indicators. GHG emissions and land-use	Adaptable to various contexts	Yes; it has already been applied to South Africa
Climate, Land-Use, Energy and Water Strategies (CLEWS)	Integrates detailed models from different tools (including WEAP, LEAP and AEZ)	National	Climate, Land, Energy and Water	Depend on the tools used for the CLEW assessment	Depend on the tools used for the CLEW assessment	Yes; if the model can be changed to evaluate the intersectoral influences of the WEF nexus components
ANEMI	Integrated assessment model	All scales	Climate, carbon cycle economy, population, land use, hydrological cycle, water demand and quality	Reveals the interconnections and feedback of each element	System dynamic simulation	Yes
Sankey diagram	Graphically represents the complex conversion pathways, flows and interdependencies between variables	All scales	WEF nexus components	Based on the data input	Adaptable to various contexts	Yes

9.5 Case Study – Buffalo River Catchment

9.5.1 Site and hydrological characteristics

The Buffalo River (BR) catchment, shown in Figure 9.3, is a sub-catchment of the Thukela Water Management Area, whose water source is in the Drakensberg region, northern KwaZulu-Natal, South Africa. The BR catchment covers an estimated 9 804 km^2 and it is located between latitude 28°42’59” S and longitude 30°38’30” E, in South Africa (uMgeni, 2020). It is the main northern tributary of the uThukela River. It flows approximately 339 km south-easterly, from the eastern escarpment (Newcastle area) and then confluences with the uThukela River (Dlamini and Mostert, 2019; uMgeni, 2020). The BR catchment is categorised as a high runoff internal sub-catchment, supplying water to numerous sectors, including irrigation, power generation, domestic, mining and bulk industries (uMgeni, 2020). There have been severe droughts in the past years, especially during 2015 and 2016, affecting livelihoods and socio-economic activities within the BR catchment and surrounding areas (uMgeni, 2020). Thus, the implications of possible CC outcomes on the BR catchment's capability to meet its water demands must be evaluated.

Figure 9.3 Schematic of the Buffalo River catchment with water demand sites and reservoirs.

The BR catchment covers the following local municipalities: (a) Newcastle, (b) Dannhauser, (c) Utrecht and (d) Nquthu. The catchment population is approximately 0.7 million, with an average population density of 79.83 per km^2. From the community census conducted in 2011 and 2016 by StatsSA (2016), the number of households in the BR catchment's local municipalities increased from 142 713 to 149 878, and the household size remained at five people per household.

9.5.2 CLEWS approach and model interaction

The CLEWS modelling framework focuses on the analysis of interactions among the climate, land, energy, and water systems, supported by quantitative studies of the interactions and use of resources; thus, it is interdisciplinary (Ramos et al., 2020). The Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE), MARKAL (an acronym for MARKet ALlocation), and Long-range Energy Alternatives Planning (LEAP) models are typical CLEWS analytical tools used for energy system analysis. LEAP is an integrated, scenario-based modelling tool (Nieves et al., 2019), well-fitting to this study's intended methodology of utilizing scenarios. Additionally, LEAP enables the tracking of energy consumption, production, and resource extraction in all sectors of the economy (Nieves et al., 2019). The Water Evaluation and Planning (WEAP) model is normally used for water system planning in CLEWS (Miralles-Wilhelm, 2016). Thus, it was used in this study. WEAP's advantage is that it is a scalable resource planning tool that allows the comparison of water supplies and demands and provides capabilities for projecting demands (Shannak et al., 2018). The selected land-use methodology for this study is the Agroecological Zones (AEZ), commonly used in CLEWS for analysing changing agricultural yields and crop production potential (Welsch et al., 2014).

In setting up for the CLEWS approach analysis, the Current Practice Approach (CPA) was established as the initial step and for comparison purposes. In the CPA, the WEAP model was used to calculate the effects of rainfall variability on streamflow and net surface water storage without explicitly considering the interlinkages between land-use and energy systems. For the CLEWS approach, the following additional interlinkages to water, energy and agricultural systems using LEAP and gAEZ, observed in Figure 9.4, were considered:

i. The irrigation water requirements to produce the projected agroecological attainable yield of the catchment's irrigated commercial crops were derived from the global AEZ land-use assessment made by the Food and Agricultural Organisation (FAO) and the International Institute of Applied Systems Analysis (IIASA).
ii. Energy demands for irrigation and household use were derived using the LEAP model.
iii. Water demands for producing LEAP energy demands were modelled in the WEAP model.

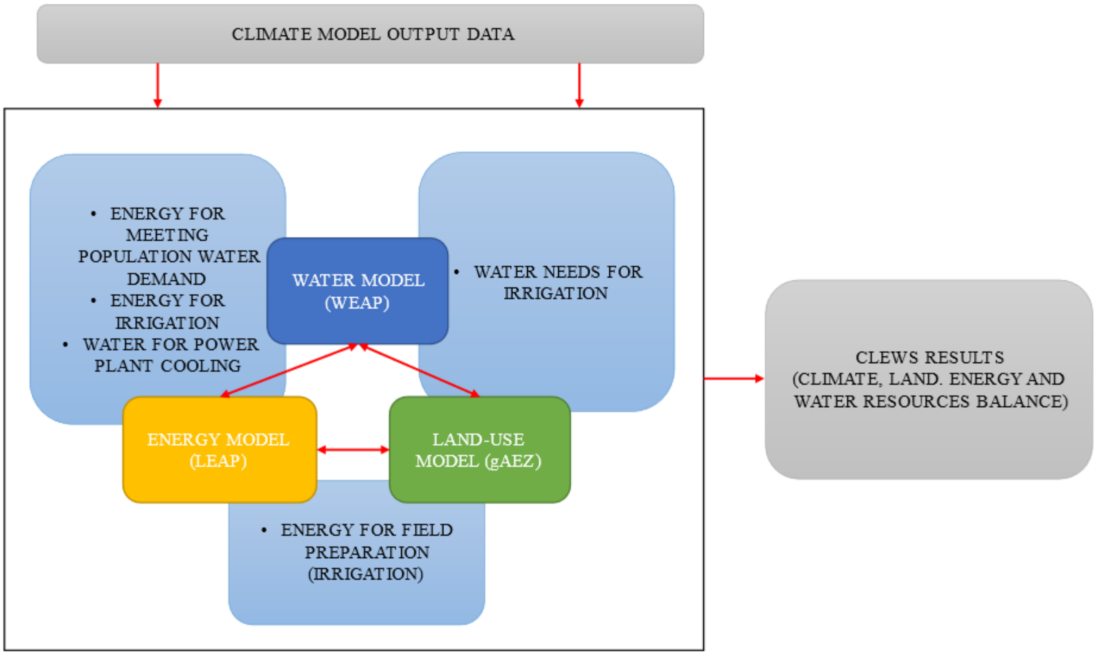

Figure 9.4 Model interactions derived from the CLEWS approach (adopted from Welsch et al., 2014).

9.5.3 Simulations

Precipitation

To investigate the overall projected changes in the BR catchment, the multi model ensemble mean approach was adopted (Tramblay et al., 2018; Hadri et al., 2022), whereby the projected changes of the 6 GCMs, obtained from the NASA Earth Exchange Global Daily Downscaled Climate Projections dataset and bias corrected using the linear scaling method, were averaged annually under both RCP4.5 and RCP8.5 scenarios. The analysis of the projections was broken into three timeframes: (a) near future (2020-2045), (b) mid-future (2046-2070), and (c) far future (2071-2100).

In the near- and mid-future periods, the average ensemble of the RCP4.5 scenario projected precipitation to remain within the historical range, with MAP increases of 0.06% and 0.32%, respectively. Decreases in variability are also modelled in the aforementioned timeframes for RCP4.5, shown by the coefficient of variation (CV) decreasing slightly from a historical value of 7.9% to 6.5% and 6.7%, respectively. However, for the far-future timeframe, a slight increase in rainfall is projected as the percent increase of MAP is 3.4%. Increased variability is also noted by the CV value increasing to 7.1%.

The average ensemble of the RCP8.5 scenario projects a slight decrease in the amount of precipitation received by the catchment in the near future, with the MAP decreasing by -2%, thus resulting in an overall MAP value of 787 mm. The rainfall variations increased slightly during this timeframe as the

CV increased from a historical value of 7.9% to 8.1%. Increases in precipitation magnitude and fluctuations in the mid- and far-future are more prominent in this climate scenario than in the RCP4.5 scenario, with the percentage increase of MAP being 4.3% and 5.4%, respectively, and the CV value reaching 8.5% in both periods. From the box-and-whisker plot in Figure 9.5, a positive skewness resulted in the far future, signifying that the frequency of low rainfall occurrences (≤ 825 mm, lower than the average of 845 mm) is expected to increase. It is also important to take note of the widened lengths of the 75th and 90th quartile whiskers in the far-future, which reflect an anticipated increase in the magnitude of extreme wet events.

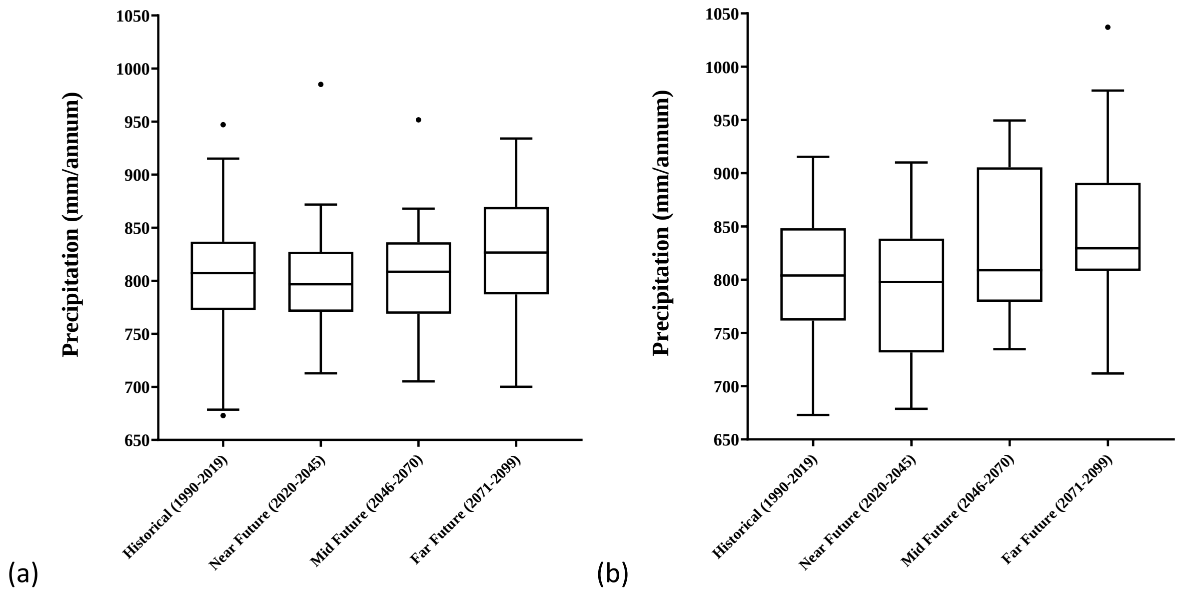

Figure 9.5 Distribution of average annual precipitation (mm/annum) for the average ensembles during the historical, near future, mid-future, and far future timeframes under the RCP4.5 scenario (a) and the RCP8.5 scenario (b).

Evapotranspiration and surface runoff

Under both climate scenario projections, for CPA and CLEWS, actual evapotranspiration (ET_A) projections are coherent with historical averages, even in the far future where the percent increases, relative to the historical value, are 0.6% and -0.3% respectively, as seen in Figure 9.6. However, the surface runoff at the BR's outlet (*Q*) projected by the CPA and CLEWS approaches, display significant differences throughout the 21st century. CLEWS projected *Q* values which are on average 8.5% lower than those projected by the CPA approach under both climate scenarios, thus flagging increased water usage and/or storage within the water supply system. Nonetheless, average *Q* volumes are still anticipated to increase under CLEWS from a historical value of 3080 Mm^3/annum to 3523 Mm^3/annum under RCP8.5 in the far future. This projected increase in *Q* is reflective of the expected increases in rainfall throughout the study period.

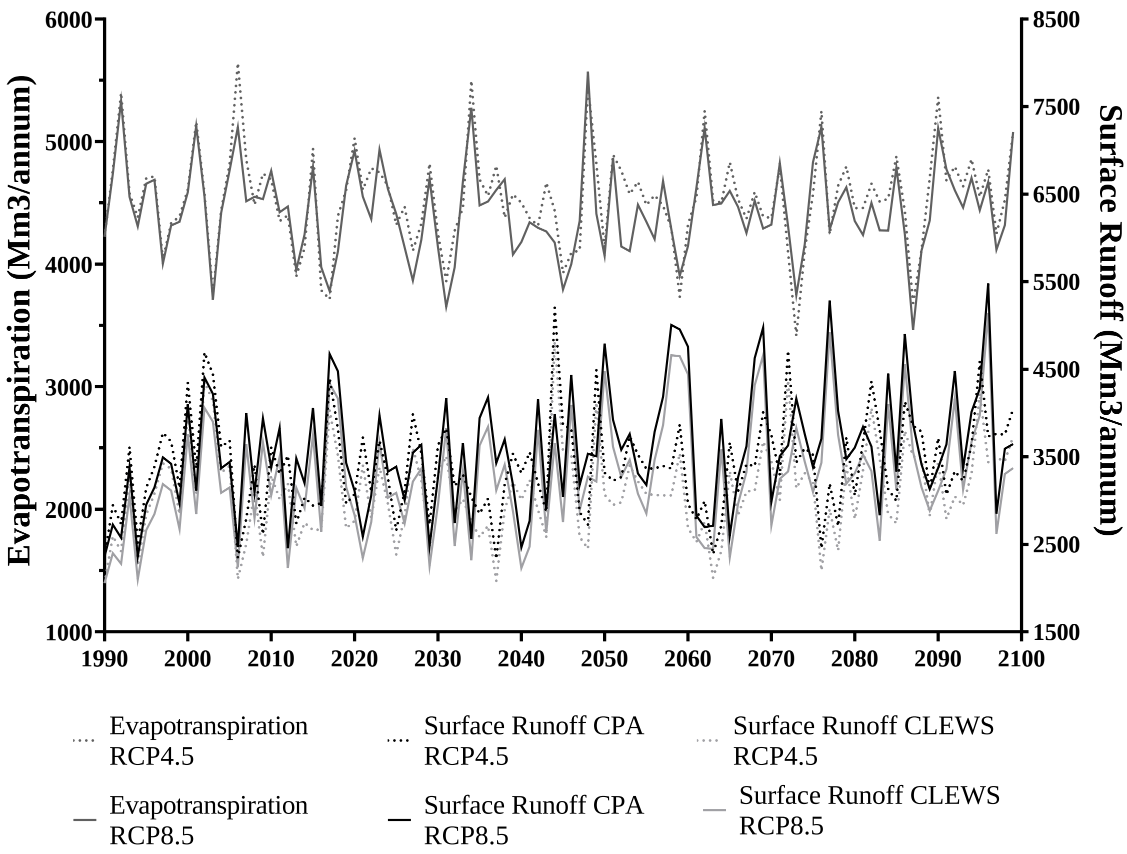

Figure 9.6 Evapotranspiration (Mm^3/annum) and surface runoff (Mm^3/annum) projections from 01/01/1990 to 31/12/2099 in the Buffalo River catchment using the CPA and CLEWS approach.

Water requirements

Irrigation water requirements

When compared to Irrigation Water Requirements (IWR) projected using the CPA approach, which assumed IWR to remain constant, the summative IWR projected using the CLEWS approach are lower by -17% and -19% in the mid- and far future under RCP4.5, while RCP8.5’s IWR are lower by -16% and -12% for the above-mentioned periods, respectively. This is attributed to the anticipated decreases in suitable hectares (ha) for crop maize and soyabean production projected by the gAEZ assessment. Even with the expected increases in IWR/ha for maize from a historical value of 280 mm to 346 mm in the RCP4.5’s far future timeframe, the decline in areas suitable for maize crop production from 11 087 ha to 9 538 ha decreased the total IWR. Similarly, for soyabean crop production, IWR are expected to increase from a historical value of 330 mm to 864 mm under RCP8.5’s far future period, however, the land (hectares) suitable for its crop production is anticipated to decrease from 3 074 ha to 1 361 ha, respectively.

Domestic and energy generation water requirements

The total domestic water demands for both CLEWS and CPA increased in the near, mid-, and far future by 30%, 59% and 89%, respectively. This is due to the increasing population of the BR catchment, more so the Newcastle local municipality, which on average, makes up 60% of the total population, and solely projected to require, on average, 25 Mm^3/annum. From the results visualized in Figure 9.7, increases in CLEWS energy demands are anticipated under climate change, also attributable to the water demand for energy generation by the increasing population.

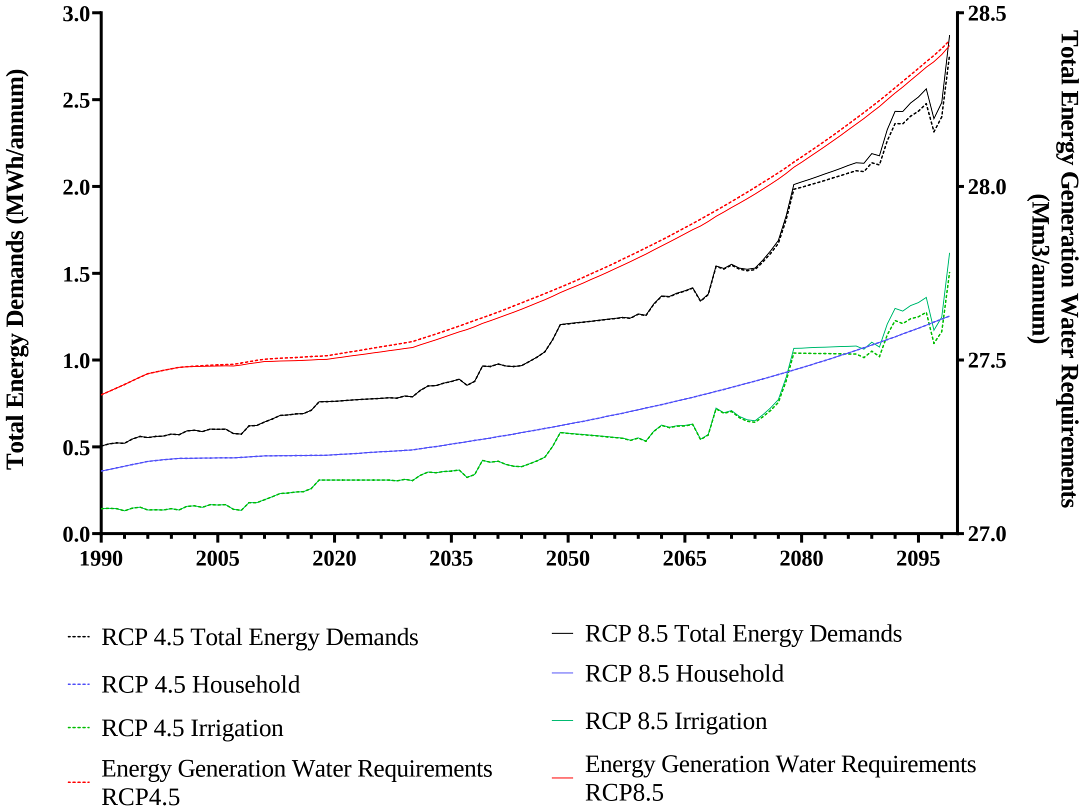

Figure 9.7 Total energy demands (MWh/annum) in the Buffalo River catchment throughout the study period (01/01/1990-31/12/2099) under the RCP4.5 and RCP8.5 scenarios.

Total water supply requirements

A significant gap is observed between the projected CPA and CLEWS RCP4.5 and RCP8.5 total water supply requirements, as seen in Figure 9.8. IWR are noted to be the reason behind this; after the CLEWS' incorporation of changes in attainable yield and their respective reduced overall IWR, a consequential reduction of total water supply requirements results. This is also in line with the national statistics of water use by sectors, which indicate that agriculture and irrigation are largely responsible for, and influence the trends of, water resource consumption in South Africa (Thopil and Pouris, 2015).

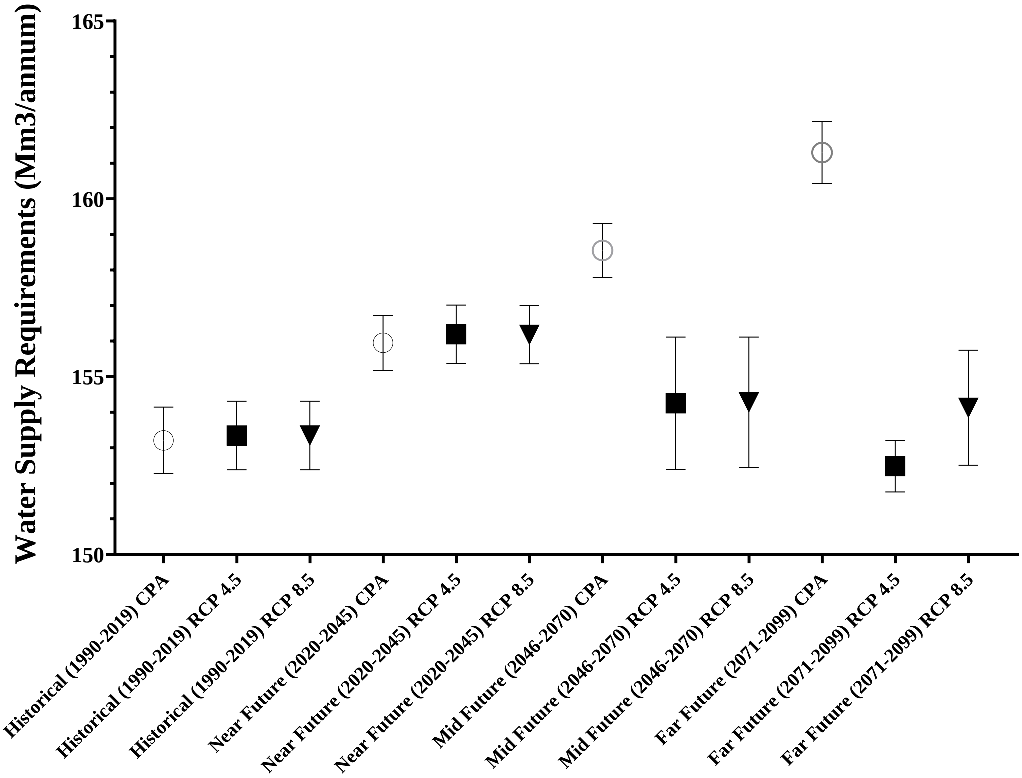

Figure 9.8 Total water supply requirements in the Buffalo River catchment under all scenarios from period 01/01/1990-31/12/2099.

Surface storage and unmet demands

The net reservoir storage (S_N) projected under CLEWS are similar to those modelled using the CPA approach, as per Figure 9.9. Such results are expected as no changes were made in the CLEWS approach to reservoir operational rules. Moreover, despite considerable expected precipitation increases in the far future, projected S_N values under both climatic scenarios show minor increases, surprisingly, even in the far future. This is primarily due to storage capacity restrictions, increased surface runoff, and for CLEWS, this highlights potential of increased water extractions from the water system.

Even though the projected S_N values are similar in both CPA and CLEWS approaches, deviations in the projected unmet demands are noted in the mid- and far-future timeframes, with the average differences being -9% and -16% respectively. The lower unmet demands simulated using CLEWS corresponds to its lower projected *Q* values, thus also highlighting increased water extractions from the catchment's supply system. Furthermore, CLEWS lower unmet demands also reflect the expected declines in total IWR, which decrease total water requirements to be met.

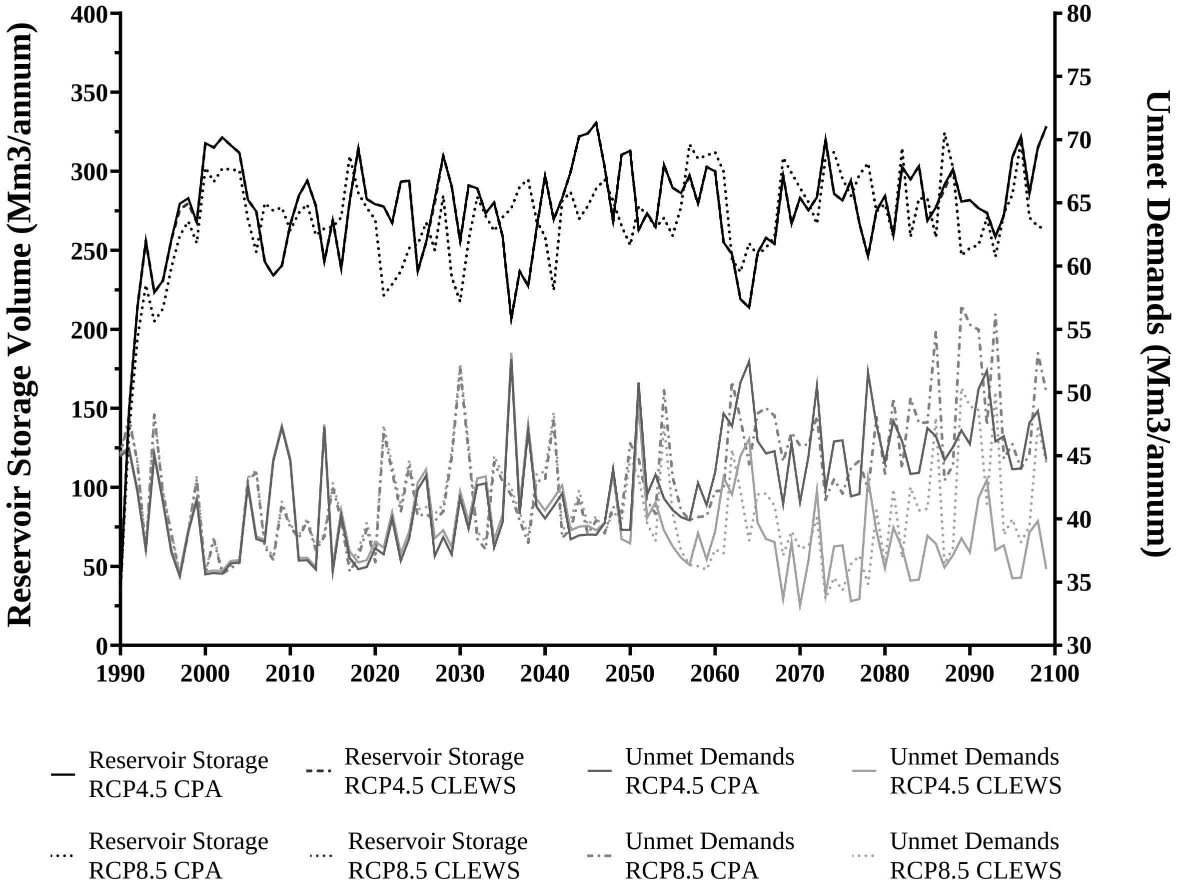

Figure 9.9 Simulated annual reservoir storage (Mm/annum) and unmet demands (Mm/annum) in the Buffalo River catchment using the CPA and CLEWS approach for period 01/01/1990 to 31/12/2099.

9.5.4 WEF Nexus water planning and allocation

From the study, it was found that the densely populated Newcastle and Dannhauser local municipalities' water demands are highly prioritized, resulting in a high reliability, or consistency, of all their demands being met, as seen in Figure 9.10. The Utrecht and Nquthu local municipalities were identified as low-priority demand sites, and the Buffalo system was found unreliable in providing their water demands. This is particularly concerning as both Nquthu and Utrecht provide a vast amount of agricultural produce for both crop and livestock purposes, and also possess potential for further agricultural expansion. Plans in reallocating water to these demand sites are encouraged to strengthen the system's reliability in meeting their needs.

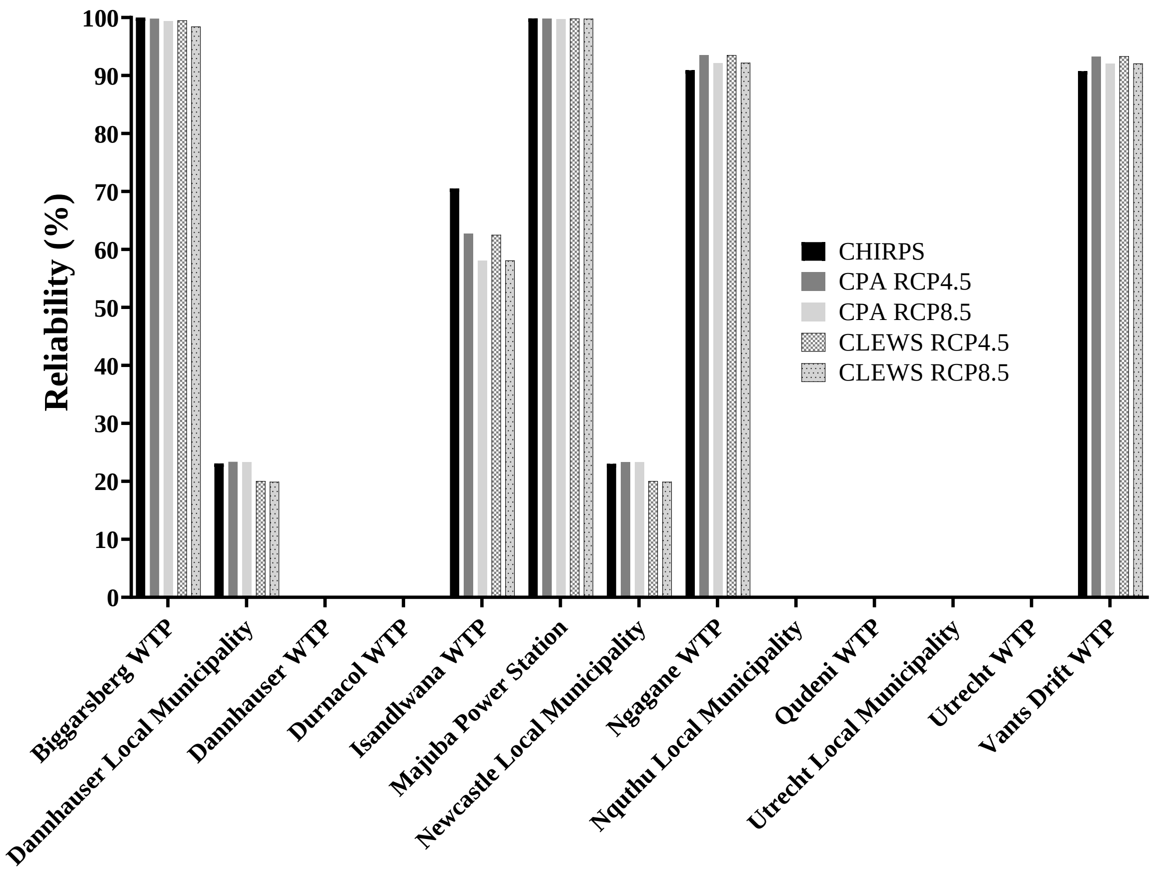

Figure 9.10 Water system supply reliability (%) throughout the study period (01/01/1990-31/12/2099) in the Buffalo River catchment.

9.6 Concluding Remarks

Water resources and CC assessments are vital for sustainable water policy framing; therefore, they should be executed in an integrative approach, looking closely at the nexus of water, energy, and food resources since they are intrinsically linked. Through investigating climate change impacts on water supply resources and their capability to meet the anticipated growing demand of WEF sectors, the study findings highlight the interconnections among climate change and the WEF nexus.

Increased rainfall magnitude and variation are to be anticipated towards the end of the 21st century, accompanied with increases in evapotranspiration and surface runoff. CC is also anticipated to decrease land suitable for agricultural production, thus propelling the summative values of irrigation water demands to decline. Such declines in the agricultural sector are a significant cause of concern for food security and the socioeconomic standing of the catchment communities, and they are expected to have a significant influence on the catchment's total water supply requirement, despite increased demands from domestic and energy generation water requirements. However, decreases in irrigation water demand are likely to benefit the domestic sector, as increases in their water allocations are projected as a result of CC. Adding to this, current water allocation plans are centred around providing a vast majority of water supplies to domestic use in high-priority regions, thus neglecting current and potential agricultural water requirements, which is problematic as the low-priority rural regions of the catchment are highly dependent and make up the majority of the agricultural sector. As such, to alleviate this inequality of water distribution, redirecting some water transmission links from the high priority demand sites to Utrecht and Nquthu, re-establishing the operational rules of WTPs, especially the Utrecht WTP, and increasing water storage targeted at providing water to the low priority area, are recommended.

10 CHAPTER 10: DOCUMENTING, PACKAGING AND PILOTING USEABLE WEF NEXUS MATERIAL FOR SOUTH AFRICA

10.1 Introduction – Different types of WEF Nexus Materials

Developing countries, particularly those experiencing significant trade-offs between water, energy, and food such as South Africa, will benefit significantly from the integrated resource management approach that the WEF nexus provides. South Africa is currently facing many challenges concerning water, energy, and food security, making it imperative that future development is anchored in WEF nexus approaches. Thus, the operationalization of the WEF nexus at various spatial and temporal scales within South Africa can address the challenges related to water, energy, and food resource insecurities (Mabhaudhi et al., 2016a; Nhamo et al., 2018).

Universities in South Africa have taken up the WEF nexus approach as an integral part of research and are involved in projects to maximize synergies between WEF sectors. Most of the existing projects have a focus on conceptual and discourse-level WEF nexus applications. The University of Cape Town has a WRC-funded project focusing on generating evidence for the WEF nexus at a local scale. It focuses on catchment and household-level analyses. The University of Stellenbosch has been developing WEF nexus proposals focusing on the Western Cape and Cape Town, particularly a city WEF nexus study. The University of KwaZulu-Natal (UKZN) has completed a WEF nexus assessment study for South Africa and is currently undertaking a WRC-funded project and looking at WEF nexus research in food systems through the Sustainable and Healthy Food Systems (SHEFS) programme. UKZN also has a project called Rural and Urban Nexus for Resilient Cities (RUNRES), which focuses on applying nexus approaches to promote the transition to a circular approach. The UKZN-led projects concentrate on the WEF nexus analytical models and the operationalization of the WEF nexus.

10.2 WEF Nexus Material Packaging

The argument for the WEF nexus has, by now, been adequately articulated given the background that by 2030 the global population will need at least 40% more water, 35% more food and 50% more energy. By 2050, a 70% increase in global food demand is predicted. Meeting the demand for food in sufficient quantities and acceptable nutritious quality underlines the importance of greater efficiencies in agricultural production systems globally (using water and energy). It is projected that by 2025, 40% of the global population will be prone to severe water stress – both physically and economic water stress.

Against this background, the WEF nexus came to the fore as a viable decision support tool, that, among other things, indicates the performance of resource utilisation and planning, establishes a quantitative relationship among interlinked resources, and indicates priority areas for intervention, aimed at establishing a balanced resource use and planning, and inclusive economic growth for sustainable development (Nhamo et al., 2020). Thus, the method is a catalyst for climate change adaptation and resilience-building by improving human well-being and attaining Sustainable Development Goals (SDGs), particularly SDGs 2, 6, and 7 (Mabhaudhi et al., 2019).

The WEF nexus has gained undivided attention in research, policy dialogue and development (Bazilian et al., 2011; Eftelioglu et al., 2017). This has seen WEF nexus being mainstreamed into thematic areas, strategies and policies by local, regional, and international institutions, governments, and organizations (SADC, 2016; GWP-SA, 2019a; GWP-SA, 2019b). The actual nature and significance of interconnections between the WEF resources are context-specific, hence the need to explore and understand the interdependence of water, energy and food security and the natural resources that underpin their security (Liu et al., 2017; Salam et al., 2017). Despite the hype of the WEF nexus agenda, several authors concur that the actual translation of the theory into practice is lagging hence the need to investigate the limited uptake of the promising approach (Byers, 2015; Daher and Mohtar, 2015; Liu et al., 2017; Galaitsi et al., 2018; McGrane et al., 2019; Nhamo et al., 2020a; Naidoo et al., 2021).

10.3 Teaching the WEF Nexus at the Vocational and Tertiary Levels

Being a relatively new concept (since about 2011) the WEF nexus comes across with many definitions and conceptualisations as users understand it differently and identify diverse utilities. For example, the WEF nexus has been called a conceptual framework, a concept, a discourse, an analytical tool, an innovation and more recently a practice. Worldwide the WEF nexus has been applied to a wide range of cases, both in space and in time. Despite its popularity, as evidenced by the exponential growth in research publications to do with the WEF nexus, its wider uptake and application have remained relatively low, both in South Africa and across the world. It has generally been applied only on a case study basis, and tools and models developed have also shown very limited application across spatial and temporal scales (Taguta et al., 2022). There is no evidence of wholesale mainstreaming of the WEF nexus as a planning tool for natural resources management. The question then arises as to why is there no wholesale uptake and application of the WEF nexus, especially in government departments mandated with natural resources management? A study was undertaken, among other, pertinent questions that included the following:

- How best can the WEF nexus be applied in the context of South Africa's problems?
- How can the WEF nexus move from theory to analysis to practice in South Africa?
- How can the WEF nexus be packaged and applied to realize the SDGs 2, 6 and 7 in South Africa?
- Are there any tertiary institutions in South Africa teaching the WEF nexus, as was the case with the Integrated Water Resources Management (IWRM) concept and practice?

The last question is particularly pertinent as it seeks to answer whether there are any higher education and tertiary institutions in South Africa involved in the teaching and learning of the WEF nexus. Answering this question requires a curriculum review to assess the current status, identify existing gaps, determine how these gaps can be filled, by who, how and when.

10.3.1 Curriculum Development, Curriculum Review and Curriculum Reform Processes

Curriculum is a course of study to be taken by students at a learning institution. Curriculum development, curriculum review and curriculum reform are three related but different processes. Curriculum development by and large implies the crafting of a (new) curriculum or programme of teaching and learning from ‘scratch’ answering the questions “what will be taught, who will be taught, and how it will be taught”. On the other hand, curriculum review generally means a curriculum exists and is now being re-looked at with the intention of improving it to serve a particular purpose which is to enhance student learning, engagement, experience and outcomes (Drummond et al., 1999). Closely related to the two is curriculum reform which is a process of making changes to the curriculum with the intention of making teaching and learning more meaningful and effective.

Several ways of undertaking curriculum development, curriculum review and curriculum reform exist, but all have some commonalities in steps. The main purpose of the review determines the depth of detail required for the individual steps. For example, one might be a cursory review of certain aspects of a curriculum that will culminate in less than a 10% change to the curriculum, and this can be compared to a detailed review of all aspects of a curriculum resulting in substantial changes to that curriculum. Table 10.1 shows the general steps followed in curriculum review, which serve as a guide. They comprise the key steps of planning, content and methods development, implementation, and evaluation.

Table 10.1: Steps in curriculum review

Step	Activity	Content
1	Need for Curriculum Review	What is the need for curriculum review?
2	Form Curriculum Review Committee	Determine who will be involved in the curriculum process
3	Terms of Reference (ToR)	Outline the ToR of the Curriculum Review Committee and the timeline for the review.
4	Undertake Curriculum Review	Attend to the following issues: • What is the current curriculum? • Who are the key stakeholders? • Who are the target leaners? • What are the target outcomes of the learning? • What are the teaching methods? • What are the assessment methods? • What are the gaps or required changes in the current curriculum?
5	Develop New/Revised Curriculum	Based on STEP 4, develop a revised or new curriculum to meet the needs of learners and expected learning outcomes.
6a	Recruit and/or Capacitate Teachers/Instructors	If needed, capacitate or recruit teachers or instructors required to teach the new or revised curriculum.
6b	Upgrade/Update Teaching Facilities/Resources	If needed, update or develop required resources, e.g. laboratories, libraries, etc.
7	Pilot New/Revised Curriculum	Pilot teach the new or revised curriculum and adjust it as needed.
8	Implement New/Revised Curriculum	With capacitated teachers and upgraded facilities implement the new or revised curriculum.
9	Monitor and Evaluate Implementation of New/Revised Curriculum	Monitor and evaluate the implementation of the new or revised curriculum.
10	Go to STEP 1	After an appropriate time period and depending on developments, go to STEP 1.

The steps listed above are generic and can be modified depending on the need for the curriculum reform. The above steps apply with regard to the current WEF nexus teaching and learning in the context of South Africa.

Embedding Water-Energy-Food Nexus into Curriculum of Tertiary Institutions

To enhance the uptake and practice of WEF nexus as a natural resource planning and management approach in South Africa, WEF nexus material will and should be included in the teaching and learning in institutions of higher and tertiary learning. This can be part of deep-scaling the WF nexus in South Africa. A parallel equivalent is the IWRM concept which has been part of higher and tertiary education in South Africa and the world and is now part of the daily operations in most departments dealing with water issues. The WEF nexus is better because it gives equal weight to the three resources of water, energy and food, ensuring their synergistic management.

The question that arises is how can this be practically undertaken in South Africa and over what period? With regard to how it can be done, a survey of WEF nexus curriculum in South Africa was undertaken and is reported herein. In terms of the timeline, this will be after the end of this research project because it is acknowledged that curriculum review and change in South Africa takes an inordinate amount of time running up to 5 years from start to finish.

The project team conducted a survey to document the teaching of WEF nexus related material at selected South African tertiary institutions. The survey used a structured questionnaire administered to 28 institutions of higher learning in South Africa. The questionnaire was administered online using Google Forms. The UKZN Humanities and Social Sciences Research Ethics Committee ethically reviewed and approved the survey as part of a more extensive WEF study (approval number HSS/1971/017D). The analysis of the results, including graphs and frequencies, was done in Google Forms. Ten completed questionnaires, representing a 36% return, were received and included in the analysis. The survey findings are discussed in the sections that follow.

Respondent details

The respondents represented a cross-section of disciplines found in academic and research institutions, i.e. senior lecturers, professors, research chairs, and research directors of learning institutions. The respondents related to various departments, most of which had an agriculture focus, environmental management centres, water, and sanitation, built environment, and bioresources engineering. Eight respondents had been involved in reviewing and developing new curricula at the undergraduate or postgraduate level. The other two respondents were not involved in curriculum development in the university system.

Characteristics of participating institutions

Figure 10.1 shows the location of the institutions involved in the survey, spanning across six of the country's nine provinces. All the participating institutions offer undergraduate, Masters and PhD degree programmes, whilst nine offer Diploma programmes, and only five provide Certificate courses.

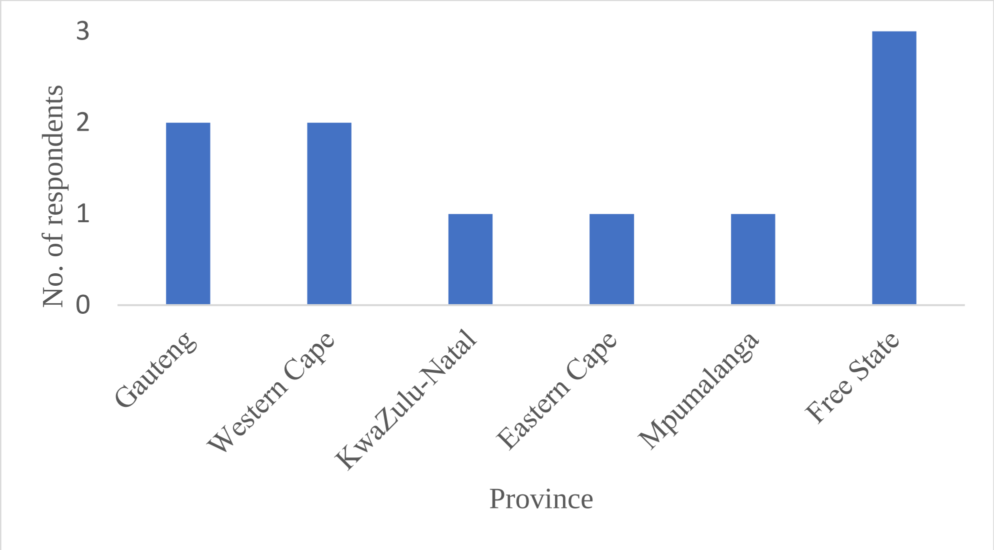

Figure 10.1 Distribution of respondents across the South Africa's provinces

Knowledge of WEF Nexus

All respondents indicated that some members of their institutions were aware of WEF Nexus. Nine out of the ten respondents had been involved in WEF Nexus research. Nine of the ten respondents also indicated that their institutions incorporated Integrated Water Resources Management (IWRM) into teaching and research.

WEF Nexus Teaching and Learning

All respondents had been involved in aspects of WEF Nexus teaching and research for periods ranging from three to 20 years. This would suggest that there is a view that WEF teaching and research was initiated earlier than the last ten years when it was popularized. Departments or centres involved in WEF Nexus teaching and learning in the various institutions were Environmental Management, Development Studies, Water Resources Management, Water and Sanitation Research, Engineering and Built Environment, Applied Sciences, South African Renewable Technology Centre, Earth Sciences, Bioresources Engineering, Transformative Agriculture and Food Systems, and Water Resources Research. WEF Nexus training is being conducted primarily at the postgraduate level in all institutions. Three institutions offered undergraduate-level degrees, four trained at the diploma level, and two indicated that WEF Nexus training is conducted at the certificate level. Figure 10.2 shows that WEF

Nexus is primarily embedded in the curriculum at the postgraduate level and less so at undergraduate, diploma and short courses.

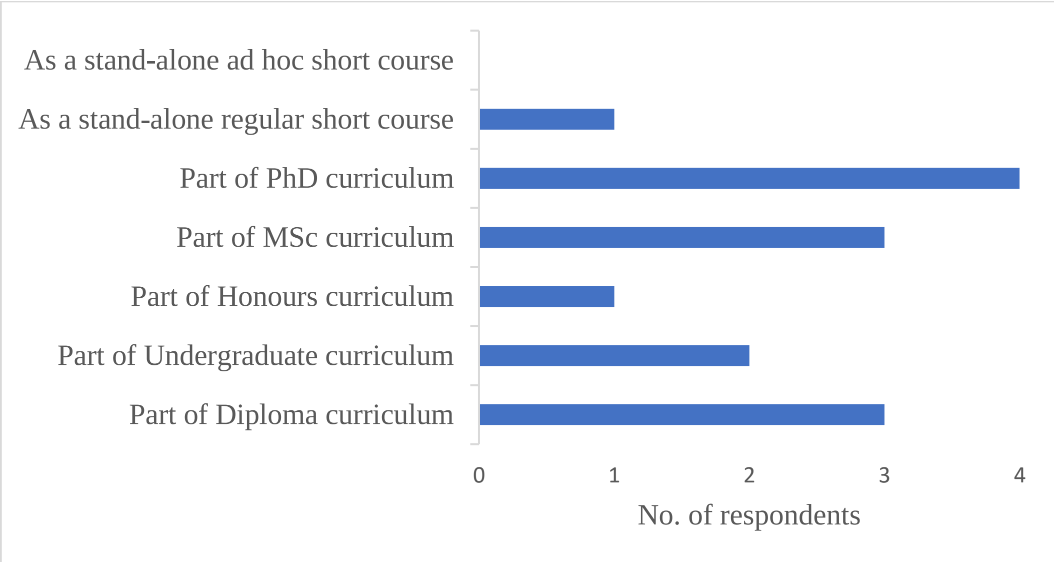

Figure 10.2 Levels at which the WEF Nexus is embedded in the curriculum

Findings also showed that most institutions focus curriculum improvement of WEF Nexus concepts, frameworks, models, and tools (Figure 10.3).

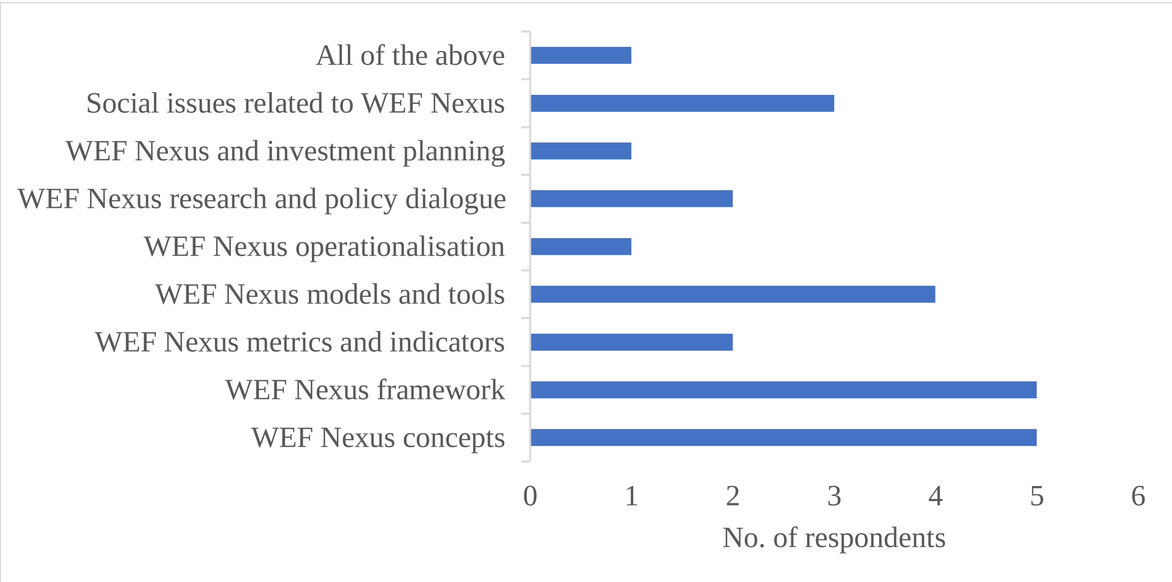

Figure 10.3 Aspects of WEF Nexus covered in the curriculum

Only two institutions had specific WEF Nexus modules: An overview of the WEF nexus concepts, WEF Nexus Master Class and WEF Nexus Winter School. Two respondents indicated that they did not have stand-alone modules precisely termed WEF Nexus, but they have modules with aspects of WEF Nexus in the curriculum. Other institutions offer modules such as Water Resources Assessment, Water Resources Management, Environmental Science, and Sustainable Development: Policy and Practice.

One respondent indicated that their institution did not offer WEF Nexus-related modules but only conducted research. Most respondents indicated that WEF Nexus is assessed through postgraduate dissertations and theses. At the same time, four respondents mentioned that they assess WEF Nexus as case studies, practical reports, or formal tests and examinations.

All respondents believe there are gaps in the teaching and learning of WEF Nexus. Seven respondents indicated that WEF Nexus has always been part of their curriculum, but they do not refer to it as WEF Nexus. In this regard, they teach aspects of water, energy, and food separately, focusing primarily on water and food. They expressed that the link across the three elements in WEF Nexus is missing in the curriculum, and there is no clarity on how the connection can be created. One respondent mentioned that although training on water was conducted across all faculties at their institution, food issues are only taught in the Faculty of Agriculture, and energy is in the Faculty of Engineering. The gap lies in how best to incorporate WEF because curriculum development is costly and time consuming. Other respondents indicated that there is very little content on WEF Nexus covered in undergraduate agricultural courses because there is inadequate space and time in the modules to have depth. One respondent indicated that their institution did not cover operationalization, systems dynamics modelling and social aspects of WEF Nexus.

Advocacy on incorporating aspects of WEF into the curriculum is needed to improve WEF Nexus teaching and learning. Respondents suggested various ways that can strengthen WEF Nexus teaching and learning. Summer schools and short courses were recommended for imparting WEF knowledge to students; conducting more research that can translate to teaching in the class; including more WEF nexus content in undergraduate courses, particularly in the third or fourth-year undergraduate teaching and at MSc by research. They also indicated the need to show the relevance of WEF to different contexts and applications and embed the learning more strongly in climate change courses instead of just meeting SDG targets.

Potential for WEF Nexus Expansion and Integration

The survey showed that WEF Nexus awareness is generally required at various learning institutions across departments and research centres because few people are working on it. Without understanding WEF, implementation will not gain traction. Since academic teaching modules are reviewed every five years, they end up missing out on topical issues within the five-year horizon. Awareness will also improve the understanding of the relevance of WEF to IWRM in a different context. Three respondents also mentioned that awareness of the WEF Nexus approach accelerates transdisciplinary research that can provide sustainable solutions to complex problems that a single discipline cannot address. In addition, all three aspects of WEF Nexus represent a critical challenge in

South Africa and many other countries, and they deserve urgent attention on strategies to deal with the challenge.

Most respondents recommended Agriculture and Environmental studies as the disciplines ideal for housing WEF Nexus teaching. One respondent indicated Heath Studies, and two others suggested Architecture, Engineering and Construction or Applied Sciences as the recommended disciplines to incorporate WEF Nexus in their curricula. Table 10.2 shows that most respondents view postgraduate studies as the targeted training level for WEF Nexus expansion or integration.

Table 10.2: Target clients or trainees for WEF Nexus expansion or integration

Academic level	No. of respondents
Certificates	3
Diplomas	6
Undergraduates	6
Postgraduates	10

Training of university academics

Most respondents think there is a need for capacity building of WEF Nexus at their institutions because of poor awareness and knowledge among academics. Areas where capacity building is required, include the relevance of WEF Nexus to different contexts, operationalization of the approach, system dynamics modelling, WEF nexus and investment planning, and WEF nexus and the practicalities of SDGs. One respondent indicated they require collaboration with institutions with more expertise and resources in the field. Interestingly, one respondent indicated that awareness across institutions is more crucial before capacity building because universities need to understand what is new in WEF Nexus and what is already being taught for buy-in. Since the implementation of WEF Nexus involves an increase in workload, there is a need for discussions on whether to employ new people to implement it or to offer training programmes to some of the junior staff to grow champions of WEF Nexus within the institutions.

Most respondents suggested that students will receive WEF Nexus courses at their institution well because it is a new approach that cuts across different aspects of ideas. Students are generally interested in learning topical issues. However, two respondents indicated that they do not believe WEF Nexus courses will be well received because students will only take up WEF Nexus courses if they see employment opportunities resulting from being skilled in them. Undergraduate students generally enrol for programmes which they believe are linked to direct and immediate access to employment opportunities. Currently, WEF Nexus issues are still new, and there is no clarity on how it fits into the employment system. Another respondent indicated that university management and the lecturers/trainers must be convinced first, based on relevance, affordability, and availability of time and space, before such knowledge can trickle down to students.

10.4 WEF Nexus Training Materials

WEF nexus short course trainings were held both virtually and in person in 2021 and 2022.

10.4.1 The WEF Nexus Winter School and Master Class

The origins of the Water-Energy-Food (WEF) Nexus Winter School and Master Class trace back to a workshop held in Pietermaritzburg in March 2020. Initially conceived as an in-person event, it was an idea shared by colleagues who then set out to make it a reality. However, the COVID-19 lockdowns in 2021 scuttled plans for the first Winter School. Adapting. It was then decided to host an online WEF Nexus Masterclass (Figure 10.4) in place of the Winter School. The Masterclass would be a success, with more than 80 participants from across the world participating in a three-day online training.

Figure 10.4 Some attendees of the WEF nexus Master Class

The Master Class has now been maintained as part of the WEF Nexus capacity development programme. It provides an introductory and foundational course to understanding WEF nexus concepts and tools. Due to the success of the Master Class, it was decided to maintain the two formats – an online MasterClass and an in-person Winter School. Attendance of the Master Class is a prerequisite for participation in the Winter School. In 2022, the Master Class was conducted from 13-15 June and has continued to be popular, attracting a global audience across Africa, Europe and the USA. The in-person Winter School (Figure 10.5) was held at the Future Africa Campus in Pretoria and

30 participants attended and spent a week learning about WEF nexus tools, applications, discourse and policy development. The WEF Nexus Winter School provides an advanced hands-on experience, focusing more on tools and applications and how these can be applied in real-world contexts, focusing on early career researchers. This WEF Nexus Masterclass and Winter School is a partnership between UKZN, the Water Research Commission, IHE-Delft, Global Water Partnership Southern Africa (GWPSA) and the Nexus Gains Initiative of the OneCGIAR. The partners have committed to supporting the two events for at least another five years.

Figure 10.5 Attendees of the WEF nexus Winter School in Pretoria 2022

Course Contents

10.4.2 WEF Nexus Master Class

The WEF Nexus Winter Masterclass introduces the state-of-the-art nexus research, presenting completed and currently ongoing cutting-edge approaches from various WEF nexus projects in the SADC region and from abroad (Appendix 2). Very little conceptual and theoretical background to the WEF nexus is presented (this is provided as background material and participants are expected to have some background in the WEF Nexus). The class emphasises on imparting practical skills that can be applied to complete WEF Nexus assessments and to support the development of appropriate policy and management responses. It specifically draws on outputs from the WEFTools project (https://wef-tools.un-ihe.org/project).

The WEF-Tools provides a structured knowledge base, qualitative and quantitative tools, dashboards, and a composite nexus index which will be co-developed, tested, validated, and refined through an interactive collaboration with stakeholders. The toolkit is intended to support the development of short-, medium- and long-term strategies for sustainable natural resource management and to inform policy and practice at river basin as well as local, national, and regional levels. The project`s outcomes provide a means for government ministries, NGOs and development agencies to assess progress towards relevant Sustainable Development Goals (SDGs), in particular, SDGs 2, 6, and 7. Thus, WEF-Tools supports policymakers across these sectors to make decisions which support environment, economy, and WEF security developments.

10.4.3 WEF Nexus Winter School

The WEF Nexus Winter School introduces the state-of-the-art nexus research and presents completed and ongoing cutting-edge research from various WEF nexus projects in the region and from abroad (Appendix 2). The Winter School is novel and innovative and also draws on WEFTools project outputs (https://wef-tools.un-ihe.org/project). Although some conceptual and theoretical background to the WEF nexus is provided, the emphasis on providing participants with practical skills that can be applied to complete WEFNexus assessments and to support the development of appropriate policy and management responses. At the end of the course, participants will be able to:

- Critique/discuss the WEF Nexus approach (strengths, weaknesses, opportunities, and threats);
- Explain the link to global challenges such as Climate and Socio-Economic Changes and SDGs achievement;
- Identify indicators that are applicable for tracking WEF security and SDGs achievement;
- Analyse the WEF interactions for different situations using WEF nexus frameworks;
- Apply specific tools to support WEF Nexus planning and management and enhance WEF nexus operationalization; and
- Develop policy recommendations for WEF nexus implementation and assess opportunities and bottlenecks.

The School followed a mixture of presentations, individual and interdisciplinary groupwork.

Both, the The WEFTools Project[4], and the Hoff’s Analytical Framework[5] were used. The latter is a high-level framework that considers some modifications to fit the WEFTools approach. The modifications are listed below:

i. *Nexus framing* creates a common, context-specific understanding of the key issues from a nexus perspective, explores the interlinkages between the different sectors and resources, and includes synergies and tradeoffs which could be relevant for the case study;

[4] **https://wef-tools.un-ihe.org/project**
[5] https://www.frontiersin.org/articles/10.3389/fenvs.2019.00048/full

ii. *Nexus opportunities* identifies how a nexus approach could add value in the respective context, e.g. by improving (cross-) resource productivity, reducing resource and environmental degradation, increasing climate resilience, and reducing human insecurities/poverty/unemployment;
iii. *Technical and economic nexus solutions assesses* and, if possible, quantifies potential benefits from the implementation of nexus approaches or "nexus savings" in the respective case study, e.g. through multi-functional production systems, municipalities or landscapes, and cross-resources and cross-sector recycling;
iv. *Stakeholders analysis* specifies the different types and levels of stakeholders involved in the case study, e.g. from public and private sector and civil society, their respective roles, and what is required for success;
v. *Framework conditions* addresses relevant conditions and context factors including type (technical solutions, policy solutions, mix of measures) scale and level (e.g. farm-level, community-level, national level, etc.) and the actual implementation of a nexus approach. It also answers questions such as: how can the nexus approach be institutionalized, i.e. how can the experience from practical implementation be considered in policy and decision making, e.g. by improved cooperation between sectors and institutions? Have any new bridging mechanisms or even new nexus institutions been established yet, including integrated SDG and/or NDC implementation? Does this contribute to improving policy coherence and if so how? Do integrated approaches contribute to innovation (e.g. via entrepreneurs and incubators, also considering relevant framework conditions outside the nexus)?
vi. *Monitoring, evaluation* and next steps define indicators and data needs for monitoring and evaluation of the implementation of the nexus approach. It builds on the understanding that nexus implementation is a process with dynamic objectives, composition of stakeholders and processes and therefore requires a self-reflexive mechanism (institutional learning mechanism and multi-loop learning) to further evolve. This section also provides an outlook to the potential of each case study for replication and upscaling.

10.4.4 Introductory WEF nexus short course

This WEF Nexus short course was proposed under the Water and Cooperation within the Zambezi River Basin (WACOZA) project as a possible introductory course suited to a whole range of WEF nexus stakeholders (see Appendix 6). Some of the aspects are covered in the two short courses already discussed above, but this is to be shorter and compact to introduce interested parties to the WEF nexus.

10.5 Concluding Remarks

The main focus of this chapter related to WEF nexus curriculum related issues, in general and specifically to South Africa. It is acknowledged that the WEF nexus argument is well known now, but still the uptake and practice of WEF nexus as a natural resources management approach is lagging behind, both in South Africa and the in world. One of the proposed approaches to enhance deep-scaling of the WEF nexus so as to improve its uptake and putting into practice is to embed it into curriculum at higher and tertiary learning institutions. Curriculum development, curriculum review and curriculum reform are related processes which must be undertaken towards curriculum change. The process goes through several steps some of which involve undertaking a needs assessment, establishing a review team and undertaking the review process, in line with the critical steps involved.

A survey was undertaken of the WEF nexus curriculum in South Africa's higher and tertiary institutions to answer questions on the who, what and how much of the WEF nexus material is covered in the certificate, diploma, and degree programmes. In conclusion, the key survey findings were that most of the surveyed institutions had some knowledge of the WEF nexus, some had already been involved in WEF nexus research for a number of years, the WEF nexus efforts were housed mainly in water related departments and programmes such as environmental sciences, water resources management, water and sanitation research, engineering and built environment, applied sciences, earth sciences, and bioresources engineering. WEF nexus research is embedded predominantly in MSc and PhD research programmes, a wide range of WEF nexus aspects are covered but the dominant ones are concepts, frameworks and the application of models and tools. Most institutions believe that the target should be the postgraduate students, but also undergraduate students, to a certain extent. The surveyed institutions indicated that they would welcome embedding WEF nexus teaching and training at their institutions.

Regarding short courses on the WEF Nexus, two of these were run in 2021 (virtual only) and 2022 (both virtual and in-person). The short courses were well received, and will be run on a regular basis in the future. The virtual Master Class was a prerequisite and feeding into the in-person Winter School. The short course was intended to be as hands-on as possible, which was achieved to a large extent, because of the case study approach used. The Winter School participants had to bring their own case studies, which made the training relevant to their circumstances. Some of the material covered in the Master Class included; introduction to nexus thinking, overview of WEF nexus index and iWEF tool, introduction to indicators, introduction to mapping WEF nexus relationships and feedback, and WEF Nexus discourse in southern Africa and financing WEF nexus investments. For the Winter School, most of the activities involved making practical what had been covered in the Master Class but also included; observing the WEF nexus in practice, introduction to WEF nexus Serious Game, WEF Nexus discourse in southern Africa and Governance framework.

11 CHAPTER 11: SUMMARY CONCLUSIONS AND RECOMMENDATIONS

11.1 Background

Globally the demand for water, food and energy is continually increasing due to rapid population and economic growth in concert with accelerated urbanisation and changing lifestyles. It is projected that by 2030 the global population will need at least 40% more water, 35% more food and 50% more energy. By 2050, a 70% increase in global food demand is predicted. South Africa has been facing severe challenges relating to water, energy and food insecurity in recent years due to the recurrence of extreme weather events such as droughts, floods, and the outbreaks of wildfires. The WEF nexus has emerged as an integral approach to sustainably manage these three resource sectors, following the convergence of ideas from various political events, academic research and reports, as well as policy papers. The challenges that South Africa is facing with respect to water, energy and food securities make it imperative that future development be anchored in WEF nexus approaches.

Several research questions arise with respect to the WEF nexus, SDGs and efficient energy use in food production in South Africa, and these include: how best can the WEF nexus be applied in the context of South Africa's problems; what policy and economic instruments are required to operationalize the WEF nexus in South Africa; what is the best spatial scale to apply the WEF nexus for maximum impact in South Africa – nationally, provincial, locally or all scales; and is there scope for upscaling and outscaling the WEF nexus in South Africa? In light of the above questions and more, the overall goal of the research project was "*To develop a WEF nexus framework, applicable WEF nexus model, indices and guidelines for the adoption and upscaling of the WEF nexus approach in South Africa with linkages to SDGs 2, 6 and 7*". The main objective was accompanied by 8 specific objectives that answered the specific questions, and hence met the main objective of the research. The research project was cognisant of the several WEF nexus research initiatives that are taking place in the SADC region as well as South Africa and thus sought synergies with these.

11.2 Summary of Findings

The main findings of the research are summarised below and are linked to the specific research questions.

i. *WEF nexus framework for South Africa*: The Mabhaudhi et al. (2019) Sustainable Livelihoods WEF nexus framework was selected for South Africa because of its particular emphasis on Sustainable Development Goals (SDGs) 2, 6 and 7.
ii. *WEF nexus model or tool for South Africa*: The Integrative WEF Analytical model (Nhamo et al., 2020) was selected for South Africa because it holistically evaluates synergies and trade-

offs to improve efficiency and productivity in resource use and management for sustainable development

iii. *Applicable metrics and indices*: The selected applicable metrics and indicators were anchored in sustainability pillars and addressed the SDGs 2, 6 and 7. For water these were, proportion of available freshwater resources per capita (availability) and proportion of crops produced per unit of water used (productivity). For energy the indicators were proportion of the population with access to electricity (accessibility) and energy intensity measured in terms of primary energy and GDP (productivity). And lastly for food these were the prevalence of moderate or severe food insecurity in the population (self-sufficiency) and proportion of sustainable agricultural production per unit area (cereal productivity).

iv. *Packaging of the WEF nexus to achieve SDGs 2, 6 and 7*: This was based on linking WEF nexus planning and SDGs encompassing five thematic themes: (a) description of nexus analytical tool, (b) defining WEF nexus sustainability indicators, (c) linking nexus planning and related SDGs indicators, and (d) periodic assessment and monitoring of SDGs performance, and (e) benefits of regular SDGs monitoring

v. *Modalities for upscaling and outscaling the WEF nexus in South Africa*: This calls for a full understanding of the expectations, challenges and recommendations for upscaling, outscaling and deep scaling of the WEF Nexus in South Africa, and then analysing the requirements of scaling in space and in time.

vi. *Assess impacts of climate change on the WEF nexus in South Africa*: Through investigating climate change impacts on water supply resources and their capability to meet the anticipated growing demand of WEF sectors, the study findings highlight the interconnections among climate change and the WEF nexus. Increased rainfall magnitude and variation are to be anticipated towards the end of the 21st century, accompanied with increases in evapotranspiration and surface runoff.

vii. *Document and package WEF nexus materials*: To enhance deep-scaling of the WEF nexus so as to improve its uptake and putting it into practice, it must be embed into curriculum at higher and tertiary learning institutions.

viii. *Pilot teach WEF nexus in South Africa*: Curriculum review is a somewhat length process, hence the WEF nexus pilot teaching was undertaken as short courses presented both virtually and in person. The short course were well received in South Africa and the region. These were WEF Nexus Master Class and WEF Nexus Winter School.

By and large all the specific research objectives of the research project were met, except the one on introducing the WEF nexus to tertiary institutions in South Africa as that is a lengthy process that can only be undertaken after this project has ended.

11.3 Concluding Remarks

The conclusions of the research are summarised below, but it is worth noting that since the research project started, a whole lot of new WEF nexus research projects have been commissioned, some of which overlap with this research project. Be that as it may, the conclusions from this research project are as follows, in line with the key research questions:

i. *WEF nexus framework*: It is conclude that the Mabhaudhi et al. (2019) Sustainable Livelihoods WEF nexus framework is an apt framework developed in South Africa for South Africa and funded by South Africa.

ii. *WEF nexus model or tool*: It is concluded that the iWEF model adequately addresses the required WEF nexus analyses for water, energy and food resources securities;

iii. *Applicable metrics and indicators*: It is concluded that the selected metrics and indicators for water, energy and food sectors adequately encapsulate the measures required for the sustainability indicators.

iv. *Packaging of WEF nexus for SDGs 2,6 and 7*: It can be concluded that linking WEF nexus planning to the SDGs 2, 6 and 7 is the most appropriate to attain the said SDGs through regular assessing and monitoring.

v. *Upscaling and outscaling the WEF nexus*: It is concluded that by understanding and analysing the scaling requirements for the WEF nexus in space and time and housing the WEF nexus in the appropriate department or unit will allow for the successful upscaling and outscaling of the WEF nexus in South Africa.

vi. *Climate change and the WEF nexus*: It is concluded that the WEF nexus can safely be used as tool for natural resource management under climate change conditions in South Africa.

vii. *Document and package WEF nexus materials*: It is concluded that materials for the WEF nexus can safely be packaged for easy usage by users of different persuasions.

viii. *Pilot teach WEF nexus in tertiary institutions*: It is concluded that efforts should be made after the end of this project to embed and pilot the training of WEF nexus related material at tertiary institutions in South Africa.

It is further concluded in general that the research project was quite ambitious in scope as it sought to answer all the questions that were important with regard to the WEF nexus around 2018. The project did very well in attempting to answer all those questions.

11.4 Recommendations

From the research conducted, the following are some of the key recommendations:

i. The next phase of WEF nexus research should focus on operationalising the approach and transitioning it from theory to practice. This should include the development of actual case studies, and real-world application of tools/indices/metrics developed thus far.

ii. The climate change impacts assessment done in this study highlighted the value of scenario analysis for long-term planning. Thus, future WEF nexus research should focus on developing integrated WEF scenarios that consider climate change and other factors.

iii. Lastly, establishing the WEF Nexus Centre of Excellence is a step in the right direction. However, it needs to be capacitated for it to play a meaningful role in setting and driving the WEF nexus research agenda for the region. There is a lot of fragmentation in research, with elements of duplication and lack of advancement. The WEF Nexus CoE could play a significant role in developing and driving a coherent and cohesive research agenda. This should be coupled with multi-level capacity development targeting individual, institutional and communities of practice

11.5 Future Research

The quest for understanding and putting into practice the WEF nexus as natural resources tool continues. Areas of possible future research include:

i. Designing funding models to get the WEF nexus to be researched, studied and taken up as popularly as the IWRM concept.

ii. Better packaging of WEF nexus materials as the subject matter moves from theory to practice.

iii. Further development of the iWEF model so that it can take a wider range of indicators from the current 6 to maybe 9 or 12 or even 15 to include other nexus issues of interest such as the environment (or ecosystems), health, land and governance.

12 REFERENCES

Ahjum, F., Merven, B., Cullis, J., Goldstein, G., Delaquil, P. & Stone, A. 2018. Development of a national water-energy system model with emphasis on the power sector for South Africa. Environmental Progress & Sustainable Energy, 37, 132-147.

Akhtar, M. K., Wibe, J., Simonovic, S. P. & Macgee, J. 2013. Integrated assessment model of society-biosphere-climateeconomy-energy system. . Journal of Environmental Modelling & Software, 49, 1-21.

Albrecht, T.R., Crootof, A. and Scott, C.A., 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters, 13(4), pp.1-28.

Allouche, J., 2011. The sustainability and resilience of global water and food systems: Political analysis of the interplay between security, resource scarcity, political systems and global trade. Food Policy 36, S3–S8. doi:10.1016/j.foodpol.2010.11.013

Anderson, W., Johansen, C. & Siddique, K. H. 2016. Addressing the yield gap in rainfed crops: a review. Agronomy for sustainable development, 36, 18.

Armendariz Sanchez, L.V., 2014. MuSIASEM testing from a SD perspective: Implications for a sustainability assessment. The University of Bergen.

Arno, A and Thomas, S. (2016). The efficacy of nudge theory strategies in influencing adult dietary behaviour: a systematic review and meta-analysis. BMC Public Health, 16(1), 1-11.

Baleta, H., Pegram, G., 2014. Water as an input in the food value chain. Understanding the Food Energy Water Nexus. Pretoria, South Africa.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J. & Yumkella, K. K. 2011. Considering the energy, water and food nexus: towards an integrated modelling approach. . Energy Policy 39, 7896–7906.

Bellezoni, R.A., Sharma, D., Villela, A.A., Pereira Junior, A.O., 2018. Water-energy-food nexus of sugarcane ethanol production in the state of Goiás, Brazil: An analysis with regional input-output matrix. Biomass and Bioenergy 115, 108–119. doi:10.1016/j.biombioe.2018.04.017

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., Mcneill, K., Neef, A., Van Ogtrop, F. & Curnow, J. 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environmental Science & Policy, 54, 389-397.

Blignaut, J., Ueckermann, L., Aronson, J., 2009. Agriculture production's sensitivity to changes in climate in South Africa : research article. S. Afr. J. Sci. 105, 61–68.

Bobbins, K. 2015. Acid Mine Drainage and tis Governance in the Gauteng City-Region. Occasional Paper. Johannesburg: GCRO.

Brunelli, M. 2015. Introduction to the Analytic Hierarchy Process. Springer, Cham, Switzerland.

Buthelezi, L. 2012. Eskom to cut water use by 260bn litres. [Internet]. Available from: https://www.iol.co.za/business-report/companies/eskom-to-cut-water-use-by-260bn-litres-1326359. [Accessed: 13/02/2020].

Butler, J. R., Rochester, W., Skewes, T. D., Wise, R. M., Bohensky, E. L., Katzfey, J and Duggan, K. (2020). How feasible is the scaling-out of livelihood and food system adaptation in Asia-Pacific Islands?. Frontiers in Sustainable Food Systems, 4, 43.

Byers, E. A. (2015). Tools for tackling the water-energy-food nexus. Change and Adaptation in Socio-Ecological Systems 2 (1). doi:10.1515/cass-2015-0019

C Le Maitre, D. C., Forsyth, G. G., Dzikiti, S. & Gush, M. B. 2016. Estimates of the impacts of invasive alien plants on water flows in South Africa. ater SA 42.

Carter, S., Gulati, M., 2014. Understanding the Food Energy Water Nexus Climate change , the Food Energy Water Nexus and food security in South Africa. Pretoria, South Africa.

Conway, D., Van Garderen, E.A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., Thurlow, J., Zhu, T., Dalin, C., 2015. Climate and southern Africa's water–energy–food nexus. Nat. Clim. Chang. 5, 837–846. doi:10.1038/nclimate2735

Daher, B. T., and Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water International 40 (5-6): 748-771. doi:10.1080/02508060.2015.1074148

Dargin, J., Berk, A. and Mostafavi, A., 2020. Assessment of household-level food-energy-water nexus vulnerability during disasters. Sustainable Cities and Society, 62, p.102366.

Davies, E and Simonovic, S. 2010. ANEMI: A New Model for Integrated Assessment of Global Change. Interdisciplinary Environmental Review 11 (2/3): 128-161.

DCGTA. 2015. uMzinyathi District Municipality (MZD): District Growth and Development Plan. KZN Department of Co-operative Governance and Traditional Affairs, Dundee, South Africa.

DEA (Department of Environmental Affairs). National Waste Information Baseline Report; DEA: Pretoria, South Africa, 2012. Available online: http://sawic.environment.gov.za/documents/1880.pdf (accessed on 2 October 2020).

DEA. 2013a. Climate Change Implications for the Water Sector in South Africa. Report No.: 2 of 6. Long-Term Adaptation Scenarios Flagship Research Programme (LTAS), Department of Environmental Affairs, Pretoria, South Africa.

DEA. 2013b. The Implications of Climate Change for the Agricultural Sector in South Africa. Long-term Adaptation Scenarios Research Programme for South Africa, Department of Environmental Affairs, Pretoria, South Africa.

District Development Model (DDM). 2021. District Development Model – To accelerate, align and integrate service delivery. https://www.cogta.gov.za/ddm/ (accessed 30/09/2021)

Dixon, MR. (2013). Trickle-down behavior analysis. Behavior Analysis in Practice, 6(2), 2.

Dlamini, N and Mostert, R. 2019. Closure Plan in Support of the Environmental Authorisation for the Proposed Prospecting Right Application for Coal, Pseudocoal, Anthracite, Sand and Clay on the Remainder of the Farm 15454, Remainder of the Farm Highvake 9311, Remainder and Portion 1 of the Farm Lowvale 15596, Remainder of the Farm Ormiston 8195, Remainder And Portion 3 of the Farm Langklip 10711 and Remainder of the Farm 16763, Under Dannhauser Local Municipality, Kwa-Zulu Natal Province. Report No.: K2017367277. Thikho Resources, Johannesburg, South Africa.

Donnenfeld, Z, Crookes, C and Hedden, S. 2018. A Delicate Balance: Water Scarcity in South Africa. Report No.: 13. Institute of Security Studies, Water Research Commission, Pretoria, South Africa.

Drummond, I., Alderson, K., Nixon, I. and Wiltshire, J. (1999) Managing curriculum change in Higher Education: realising good practice in key skills development.

Duraiappah, A. K. 1998. Poverty and Environmental Degradation: A Review and Analysis of the Nexus. World Development, 26, 2169-2179.

DWS 2013. Chapter 11: International cooperation and trans-boundary water course management. National Water Resource Strategy.

DWS 2015. Construction of dams fast tracked. Department of Water & Sanitation.

Eftelioglu, E., Jiang, Z., Tang, X., and Shekhar, S. (2017). "The Nexus of Food, Energy, and Water Resources: Visions and Challenges in Spatial Computing," in Advances in Geocomputation. Advances in Geographic Information Science, ed. Griffith, D. A., Chun, Y. Dean., Denis J (Cham:

Springer International Publishing), 5-20. doi.org/10.1007/978-3-319-22786-3_2

ESKOM. 2013a. Integrated Report. [Internet]. Available from: http://overendstudio.co.za/online_reports/eskom_ar2013/pdf/full.pdf. [Accessed: 25/02/2021].

ESKOM. 2013b. Water Management [Internet]. Available from: http://www.eskom.co.za/c/article/240/water-management. [Accessed: 25/02/2021].

ESKOM. 2018. Water Supply Factsheet. Eskom Primary Energy Division with Risk and Sustainability Division, Johannesburg, South Africa.

ESKOM. 2020. Affirmation That record Requested Does Not Exist – Kendal Compliance Quest. [Internet]. Available from: https://cer.org.za/wp-content/uploads/2020/05/Formal-Response-PAIA-ref-0087-Man-Affirmation-that-records-does-not-exist.pdf. [Accessed: 20/12/2022].

ESKOM. 2022. Prolonged Loadshedding Will Continue to be Implemented over the Next Few Months as Major Capital Projects and Repairs Reduce Available Generation Capacity. [Internet]. Available from: https://www.eskom.co.za/prolonged-loadshedding-will-continue-to-be-implemented-over-the-next-few-months-as-major-capital-projects-and-repairs-reduce-available-generation-capacity/. [Accessed: 20/12/2022].

Fader, M., Cranmer, C., Lawford, R. and Engel-Cox, J., 2018. Toward an understanding of synergies and trade-offs between water, energy, and food SDG targets. *Frontiers in Environmental Science*, 6(112), pp.1-11.

FAO, 2014. The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture. Rome, Italy.

FAO 2016. Food and Agriculture Organaization: Key to achieving the 2030 Agenda for Sustainable Development. Italy, Rome: The Food and Agriculture Organization of the United Nations

FAO. 2017. Food security indicators [Online]. Available: http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/#.WwPxxMsh1hF [Accessed 22 May 2018].

Galaitsi, S., Veysey, J., and Huber-Lee, A. (2018). Where is the added value? A review of the water-energy-food nexus literature. Somerville: Stockholm Environment Institute.

Goga, S. & Pegram, G. 2014. Water, energy and food: A review of integrated planning in South Africa. Understanding the Food Energy Water Nexus. South Africa.

GoZa. 2015. South African Government National Water Security. [Internet]. Available from: https://www.gov.za/about-government/government-programmes/national-water-security-2015. [Accessed: 09/03/2020].

Graham, L, Andersson, L, Horan, M, Kunz, R, Lumsden, T, Schulze, R, Warburton, M, Wilk, J and Yang, W. 2011. Using Multiple Climate Change Projections for Assessing Hydrological Response to Climate Change in the Thukela River Basin, South Africa. Physics and Chemistry of the Earth 36 (14-15): 727-735.

Gulati, M., Jacobs, I., Jooste, A., Naidoo, D., Fakir, S., 2013. The Water–energy–food Security Nexus: Challenges and opportunities for food security in South Africa. Aquat. Procedia 1, 150–164.

Gundel, S, Hancock, J and Anderson, S. (2001). Scaling up strategy for research in natural resource management. A comparative review. Natural Resource Institute. Chatham, GB.

Gupta, A. D. 2017. Water-Energy-Food (WEF) Nexus and Sustainable Development. Water-Energy-Food Nexus: Principles and Practices, 229, 223.

Hadri, A, Saidi, M, ElKhalki, E, Aachrine, B and Saouabe, T. 2022. Integrated Water Management Under Climate Change Through the Application of WEAP Model in a Mediterranean Arid Region. Journal of Water and Climate Change 13 (6): 2414.

Herrfahrdt-Pähle, E. 2010. South African Water Governance between Administrative and Hydrological Boundaries. Climate and Development 2 (2): 111-127.

Hoff, H., 2011. Understanding the nexus: Background paper for the Bonn2011 Conference.

Hoffman, T. & Ashwell, A. 2018. Land degradation: Northern Cape. Provincial Fact Sheet. Cape Town.

Hua, E., Wang, X., Engel, B.A., Sun, S. and Wang, Y., 2020. The competitive relationship between food and energy production for water in China. Journal of Cleaner Production, 247, p.119103.

Hughes, A and Kitson, M. (2012). Pathways to impact and the strategic role of universities: new evidence on the breadth and depth of university knowledge exchange in the UK and the factors constraining its development. Cambridge Journal of Economics, 36(3), 72-750.

IRENA 2015. Renewable Energy in the Water, Energy & Food Nexus.

Jones, K and Bice, S. (2021). Research for impact : three keys for research implementation. Policy Design and Practice, 1(1): 1–21.https://doi.org/10.1080/25741292.2021.1936761

Karabulut, A.A., Crenna, E., Sala, S., Udias, A., 2018. A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. J. Clean. Prod. 172, 3874–3889. doi:10.1016/j.jclepro.2017.05.092

Keairns, D. L., Darton, R. C. & Irabien, A. 2016. The Energy-Water-Food Nexus. Annu Rev Chem Biomol Eng, 7, 239-62.

Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. B Biol. Sci. 365, 2793–2807. doi:10.1098/rstb.2010.0149

Knight, J. 2016. Water Resources in South Africa. In: The Geography of South Africa. Springer Cham, South Africa.

Laspidou, C., Mellios, N., Kofinas, D., 2019. Towards Ranking the Water–Energy–Food–Land Use–Climate Nexus Interlinkages for Building a Nexus Conceptual Model with a Heuristic Algorithm. Water 11, 306. doi:10.3390/w11020306

Leketa, K and Abiye, T. 2019. Modelling the Impacts of Climatic Variables on the Hydrology of the Upper Crocodile River Basin. Environmental Earth Sciences 78 (12): 358-374.

LGCCP. 2018. Amajuba District Municipality: Climate Change Vulnerability Assessment and Response Plan. Version 2. Local Government Climate Change Support Program (LGCCP), Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ), Pretoria, South Africa.

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R. et al. (2017). Challenges in operationalizing the water–energy–food nexus. Hydrological Sciences Journal 62 (11): 1714-1720. doi:10.1080/02626667.2017.1353695

Lobell, D.B.D., Burke, M.M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science (80-.). 319, 607–610. doi:10.1126/science.1152339

López-Diaz, D.C., Lira-Barragán, L.F., Betzabe González-Campos, J., Serna-González, M., El-Halwagi, M.M., Ponce-Ortega, J.M., 2018. Optimal Supply Chain for Biofuel Production under the Water-Energy-Food Nexus Framework. pp. 1903–1908. doi:10.1016/B978-0-444-64241-7.50312-8

Mabhaudhi, T., Chibarabada, T. & Modi, A. 2016a. Water-Food-Nutrition-Health Nexus: Linking Water to Improving Food, Nutrition and Health in Sub-Saharan Africa. International Journal of Environmental Research and Public Health, 13.

Mabhaudhi, T., Mpandeli, S., Madhlopa, A., Modi, A. T., BACKEBERG, G. & NHAMO, L. 2016b. Southern Africa's Water-Energy Nexus: Towards Regional Integration and Development. Water, 8.

Mabhaudhi, T., Nhamo, L., Mpandeli, S., Nhemachena, C., Senzanje, A., Sobratee, N., Chivenge, P.P., Slotow, R., Naidoo, D., Liphadzi, S., Modi, A.T., 2019. The Water–Energy–Food Nexus as a Tool to

Transform Rural Livelihoods and Well-Being in Southern Africa. Int. J. Environ. Res. Public Health 16, 2970. doi:10.3390/ijerph16162970

Mabhaudhi, T., Simpson, G., Badenhorst, J., Mohammed, M., Motongera, T., Senzanje, A., Jewitt, A., 2018. Assessing the State of the Water-Energy-Food (WEF) Nexus in South Africa (K5/2790). Pretoria, South Africa.

Makou, G. 2017. #5facts: Water in South Africa. [Internet]. Africa Check. Available from: https://africacheck.org/reports/5facts-water-south-africa/. [Accessed: 09/03/2020].

Martin, B and Fischer, R. 2012. The Energy-Water Nexus: Energy Demands on Water Resources. EMG Water and Climate Change Research Series, Cape Town, South Africa.

Martinez-Hernandez, E., Leach, M. & Yang, A. 2017a. Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. Applied Energy, 206, 1009-1021.

Martinez-Hernandez, E., Samsatli, S., 2017b. Biorefineries and the food, energy, water nexus—towards a whole systems approach to design and planning. Curr. Opin. Chem. Eng. 18, 16–22.

Mayne, J. (2017). Theory of change analysis: Building robust theories of change. Canadian Journal of Program Evaluation, 32(2).DOI: https://doi.org/10.3138/cjpe.31122

McGrane, S. J., Acuto, M., Artioli, F., Chen, P-Y., Comber, R., Cottee, J. et al. (2019). Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. The Geographical Journal 185 (4): 419-431. doi:10.1111/geoj.12256

McNamara, I, Nauditt, A, Penedo, S and Ribbe, L. 2018. NEXUS Water-Energy-Food Dialogues Training Material: Introduction to the Water-Energy-Food Security (WEF) NEXUS. Training Unit 01. The Nexus Dialogue Programme, Bonn and Eschborn,Germany.

Middleton, C., Allouche, J., Gyawali, D., Allen, S., 2015. The rise and implications of the water-energy-food nexus in Southeast Asia through an environmental justice lens. Water Altern. 8, 627–654.

Miralles-Wilhelm, F. 2016. Development and Application of Integrative Modeling Tools in Support of Food-Energy-Water Nexus Planning – A Research Agenda. Journal of Environmental Studies and Sciences 6 (1): 3-10.

Mnguni, P., Van Vliet, B., Spaargaren, G., Nakirya, D., Osuret, J., Isunju, J.B., Ssekamatte, T. and Mugambe, R., 2020. What could go wrong with cooking? Exploring vulnerability at the water, energy and food Nexus in Kampala through a social practices lens. Global Environmental Change, 63, p.102086.

Moore, ML. (2004). Scaling out, scaling up, scaling deep: strategies of non-profits in advancing systemic social innovation. Journal of Corporate Citizenship, (58), 67-84.

Mpandeli, S., Naidoo, D., Mabhaudhi, T., Nhemachena, C., Nhamo, L., Liphadzi, S., Hlahla, S., Modi, A.T., 2018. Climate change adaptation through the water-energy-food nexus in Southern Africa. Int. J. Environ. Res. Public Health. doi:10.3390/ijerph15102306

Mu, E and Pereyra-Rojas, M. 2017. Understanding the Analytic Hierarchy Process. In: Practical Decision Making. SpringerBriefs in Operations Research. Springer, Cham.

Nahman, A., De Lange, W., Oelofse, S. & Godfrey, L. 2012. The costs of household food waste in South Africa. Waste Management, 32, 2147-2153.

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., Slotow, R., Jacobson, M., Modi, AT., Mabhaudhi, T. (2021): Operationalising the water-energy-food nexus through the theory of change. Renewable and Sustainable Energy Reviews 149 (2021) 111416 https://doi.org/10.1016/j.rser.2021.111416

Nhamo, L., Chilonda, P., 2012. Water and agriculture vulnerability to climate change and adaptive capacity in southern Africa, in: WISA (Water Institute of Southern Africa) Biennial Conference on Water Footprints. Cape Town, South Africa.

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A. et al. 2020. 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

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S., Modi, A.T., 2019b. Sustainability Indicators and Indices for the Water-Energy-Food Nexus for Performance Assessment: WEF Nexus in Practice – South Africa Case Study. doi:10.20944/PREPRINTS201905.0359.V1

Nhamo, L., Ndlela, B., Nhemachena, C., Mabhaudhi, T., Mpandeli, S., Matchaya, G., 2018. The water-energy-food nexus: Climate risks and opportunities in Southern Africa. Water (Switzerland). doi:10.3390/w10050567.

Nhemachena, C., Matchaya, G., Nhemachena, C. R., Karuaihe, S., Muchara, B. & Nhlengethwa, S. 2018. Measuring Baseline Agriculture-Related Sustainable Development Goals Index for Southern Africa. Sustainability, 10, 849.

Nieves, J, Aristizabal, A, Dyner, I, Baez, O and Ospina, D. 2019. Energy Demand and Greenhouse Gas Emissions Analysis in Colombia: A LEAP Model Application. Energy (169): 380-397.

Ofoegbu, C, Chirwa, P, Francis, J and Babalola, F. 2017. Assessing Vulnerability of Rural Communities to Climate Change: A Review of Implications for Forest-Based Livelihoods in South Africa. International Journal of Climate Change Strategies and Management.

Ololade, O. O., Esterhuyse, S. & Levine, A. D. 2017. The Water-Energy-Food Nexus from a South African Perspective. Water-Energy-Food Nexus. John Wiley & Sons, Inc.

Ozturk, I. 2017. The dynamic relationship between agricultural sustainability and food-energy-water poverty in a panel of selected Sub-Saharan African Countries. Energy Policy, 107, 289-299.

Pardoe, J., Conway, D., Namaganda, E., Vincent, K., Dougill, A.J., Kashaigili, J.J., 2018. Climate change and the water–energy–food nexus: insights from policy and practice in Tanzania. Clim. Policy 18, 863–877. doi:10.1080/14693062.2017.1386082

Parra, V, Fuentes-Aguilera, P and Munoz, E. 2018. Identifying Advantages and Drawbacks of Two Hydrological Models Based on a Sensitivity Analysis: A Study in Two Chilean Watersheds. Hydrological Sciences Journal 63 (12): 1831-1843.

Pereira, L.M., 2014. The future of South Africa's food system: What is research telling us. SA Food Lab. South Africa.

Pherali, T and Lewis, A. (2019). Developing global partnerships in higher education for peacebuilding: a strategy for pathways to impact. Higher Education, 78(4), 729-744.

Pittock, J., Orr, S., Stevens, L., Aheeyar, M. and Smith, M., 2015. Tackling trade-offs in the nexus of water, energy and food. Aquatic Procedia, 5, pp.58-68.

Qureshi, MA. (2008). Challenging trickle-down approach: Modelling and simulation of public expenditure and human development–the case of Pakistan. International Journal of Social Economics. 35(4): 269-282.

Ramos, EP, Howells, M, Sridharan, V, Engström, RE, Taliotis, C, Mentis, D, Gardumi, F, Strasser, Ld, Pappis, I, Balderrama, GP, Almulla, Y, Beltramo, A, Ramirez, C, Sundin, C, Alfstad, T, Lipponen, A, Zepeda, E, Niet, T, Quirós-Tortós, J, Angulo-Paniagua, J, Shivakumar, A, Ulloa, S and Rogner, H. 2020. The Climate, Land, Energy, and Water Systems (CLEWs) Framework: A Retrospective of Activities and Advances to 2019. Environmental Research Letters 16 (3): 033003.

REDIS. 2018. Location and Contracted Capacities of Renewable Energy Projects in South Africa

[Online]. South Africa: Deparment of Energy. [Accessed 15 May 2018].
Rice, D and Sheridan, S. (2014). Organizational Inclusiveness: A Trickle Down Approach and the role of Supervisor Political Skill. In Academy of Management Proceedings (Vol. 2014, No. 1, p. 17723). Briarcliff Manor, NY 10510: Academy of Management.
Riddell, D and Moore, ML. (2015). Scaling out, Scaling up, Scaling deep: Advancing systemic social innovation and the learning processes to support it. JW McConnell Family Foundation and Tamarack Institute, Toronto and Waterloo, ON.
Ringler, C., Bhaduri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5, 617–624.
RISDP, Regional Indicative Strategic Development Plan (RISDP), 2015. Regional Indicative Strategic Development Plan. Gaborone, Botswana.
Rogers, E. M. (1995). Diffusion of Innovations: modifications of a model for telecommunications. In Die diffusion von innovationen in der telekommunikation (pp. 25-38). Springer, Berlin, Heidelberg.
RSA 1996. Constitution of the Republic of South Africa No. 108 of 1996. Government Printer Pretoria.
Saaty, RW. 1987. The analytic hierarchy process-what it is and how it is used. Mathematical Modelling 9 (3-5): 161-176.
Saaty, TL and Vargas, LG. 2012. Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. Springer, New York.
Salam, A. P., Shrestha, S., Pandey, V. P., and Anal, A. K. (2017). Water-Energy-Food Nexus: Principles and Practices. Hoboken: American Geophysical Union. doi:10.1002/9781119243175
Sandel, B., and A. B. Smith. 2009. Scale as a lurking factor: incorporating scale-dependence in experimental ecology. Oikos 118: 1284-1291.
Schlenker, W., Lobell, D.D.B.D., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 14010.
Schlör, H., Venghaus, S. & Hake, J.-F. 2018. The FEW-Nexus city index – Measuring urban resilience. Applied Energy, 210, 382-392.
Schreiner, B., Baleta, H., 2015. Broadening the Lens: A Regional Perspective on Water, Food and Energy Integration in SADC. Aquat. Procedia 5, 90–103. doi:10.1016/j.aqpro.2015.10.011
Schulze, R and Kunz, R. 2010. Climate Change 2010 and Kikuyu Yields. In: Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa.
Schulze, R and Taylor, M. 2016. Net Irrigation Demands in South Africa and Climate Change. In: Handbook for Farmers, Officials and Other Stakeholders on Adaptation to Climate Change in the Agricultural Sector within South Africa. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa.
SEACMEQ 2017. The SACMEQ IV Project in South Africa: A Study of the Conditions of Schooling and the Quality of Education. Pretoria.
Senzanje, A. Mudhara, M. Tirivamwe, T. (2021). The Water-Energy-Food Nexus as an Approach for Achieving Sustainable Development Goals 2 (food), 6 (water) and 7 (energy). In "Water-Energy-Food Nexus Narratives and Resources Securities". Eds: Tafadzwa Mabhaudhi, Aidan Senzanje, Albert T Modi, Graham WP Jewith, Festo Massawe. Elsevier Publ., Ma, USA (in press)
Shahbaz, M., Tiwari, A.K., Nasir, M., 2013. The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa. Energy Policy 61, 1452–1459.

Shannak, S, Mabrey, D and Vittorio, M. 2018. Moving from Theory to Practice in the Water-Energy-Food Nexus: An Evaluation of Existing Models and Frameworks. Water-Energy Nexus 1 (1): 17-25.

Shezi, M and Ngcoya, M. 2016. Adaptation to the Impacts of Climate Change on Agriculture in eThekwini: A Literature Review. Report No.: 7. School of Built Environment and Development Studies, University of KwaZulu-Natal, South Africa.

Simpson, G.B., Badenhorst, J., Jewitt, G.P.W., Berchner, M., Davies, E., 2019. Competition for Land: The Water-Energy-Food Nexus and Coal Mining in Mpumalanga Province, South Africa. Front. Environ. Sci. 7. doi:10.3389/fenvs.2019.00086

Simpson, G. and Berchner, M. 2017. Water-energy nexus-Measuring integration: towards a water-energy-food nexus index. Water Wheel, 16, 22-23.

Simpson, G., Jewitt, G., Becker, W., Badenhorst, J., Neves, A., Rovira, P., & Pascual, V. 2020a. The Water-Energy-Food Nexus Index: A Tool for Integrated Resource Management and Sustainable Development.

Simpson, G.B. and Jewitt, G.P., 2019. The development of the water-energy-food nexus as a framework for achieving resource security: A review. Frontiers in Environmental Science, 7, pp.8.

Simpson, G.B., Jewitt, G.P., and Badenhorst, J., 2020. Development of water-energy-food nexus index and its application to south africa and the southern African development community. Water research commission Report No. 2959/1/19.

Sinyolo, S., Mudhara, M. and Wale, E., 2014. The impact of smallholder irrigation on household welfare: The case of Tugela Ferry irrigation scheme in KwaZulu-Natal, South Africa. Water SA, 40(1), pp.145-156.

Singh, N, Anand, B and Khan, M. 2018. Micro-level Perception to Climate Change and Adaptation Issues: A Prelude to Mainstreaming Climate Adaptation into Developmental Landscape in India. Natural Hazards 92 (3): 1287-1304.

Smajgl, A., Ward, J., Pluschke, L., 2016. The water–food–energy Nexus–Realising a new paradigm. J. Hydrol. 533, 533–540.

Sparks, D, Madhlopa, A, Keen, S, Moorlach, M, Dane, A, Krog, P and Dlamini, T. 2014. Renewable Energy Choices and Their Water Requirements in South Africa. Journal of Energy in Southern Africa 25 (4): 80-92.

Statistics South Africa (STATSSA)., 2019. The extent of food security in South Africa. http://www.statssa.gov.za/?p=12135 (accessed 10 December 2019)

Steynor, A, Hewitson, B and Tadross, M. 2009. Projected Future Runoff of the Breede River under Climate Change. Water SA 35 (4): 433-440.

Stockholm Environment Institute, 2012. WEAP (“Water Evaluation And Planning” system) is a user-friendly software tool that takes an integrated approach to water resources planning. [WWW Document]. URL https://www.weap21.org/

Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., Vamvakeridou-Lyroudia, L., Savić, D., Laspidou, C., Brouwer, F., 2018. Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The SIM4NEXUS approach. Water 10, 139.

Tälle, M., Wiréhn, L., Ellström, D., Hjerpe, M., Huge-Brodin, M., Jensen, P., Lindström, T., Neset, T.S., Wennergren, U. and Metson, G., 2019. Synergies and Trade-Offs for Sustainable Food Production in Sweden: An Integrated Approach. Sustainability, 11(3), p.601.

Taguta, C, Kiala, Z, Bangira, T, Nhamo, L, Senzanje, A and Tafadzwanashe, M. 2022a. iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical model. [Internet].

Centre for Transformative Agriculture and Food Systems (CTAFS), University of KwaZulu-Natal (UKZN). Available from: https://iwef.app. [Accessed: 23 December 2022].

Taguta, C., Senzanje, A., Kiala, Z., Malota, M., Mabhaudhi, T. 2022b. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. Front. Water, 25 March 2022. Sec. Water and Human Systems. https://doi.org/10.3389/frwa.2022.837316

THE WORLD BANK 2016. Southern Africa Energy-Water Nexus.

THE WORLD BANK. 2018. Indicators [Online]. Available: https://data.worldbank.org/indicator/ [Accessed 22 May 2018].

Thopil, G and Pouris, A. 2015. Water Usage Forecasting in Coal-Based Electricity Generation: The Case of South Africa. Energy Procedia 75 2813-2818.

Tramblay, Y, Jarlan, L, Hanich, L and Somot, S. 2018. Future Scenario of Surface Water Resources Availability in North African Dams. Water Resources Management 32 (4): 1291-1306.

uMgeni. 2020. Infrastructure Master Plan 2020 (2020/2021-2050/2051): Buffalo System. UMgeni Water, Pietermaritzburg, South Africa.

UN DESA. 2013. Global Climate, Land, Energy & Water Strategies [Online]. Available: https://unite.un.org/sites/unite.un.org/files/app-globalclews-v-1-0/landingpage.html [Accessed 21 May 2018].

UNDP 2015. Sustainable development goals.

Valenzo, T., Broeckelman-Post, MA. Parcel, ES. (2015). Communication Pathways. Communication Faculty Publications. Paper 20. University of Dayton. OH, USA.

vanNiekerk, A, Jarmain, C, Goudriaan, R, Muller, S, Ferreira, F, Munch, Z, Pauw, T, Stephenson, G and Gidson, L. 2018. An Earth Observation Approach towards Mapping Irrigated Areas and Quantifying Water Use by Irrigated Crops in South Africa. [Internet]. Water Research Commission. Available from: http://www.wrc.org.za/wp-content/uploads/mdocs/TT%20745%20Final%20Report%20reprint%2025%2005%2018.pdf. [Accessed: 13/02/2020].

Von Bormann, T., Gulati, M., 2014. The food energy water nexus: Understanding South Africa’s most urgent sustainability challenge. WWF-SA, South Africa 1–35.

Warburton, M. 2012. Challenges in Modelling Hydrological Responses to Impacts and Interactions of Land Use and Climate Changes. Unpublished PhD Dissertation thesis, School of Bioresources, Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Wassung, N. 2010. Water Scarcity and Electricity Generation in South Africa. Unpublished PhD Dissertation thesis, School of Public Management and Planning, University of Stellenbosch, South Africa.

Welsch, M, Hermann, S, Howells, M, Rogner, H, Young, C, Ramma, I, Bazilian, M, Fischer, G, Alfstad, T, Gielen, D, Blanc, D, Rohrl, A, Steduto, P and Muller, A. 2014. Adding Value with CLEWS – Modelling the Energy System and its Interdependencies for Mauritius. Applied Energy 113 1434-1445.

Weiss, CH. (1995). "Nothing as Practical as Good Theory: Exploring Theory-based Evaluation for Comprehensive Community Initiatives for Children and Families." In New Approaches to Evaluating Community Initiatives: Concepts, Methods, and Contexts, ed. James Connell et al. Washington, DC: Aspen Institute.

Westley, F., Antadze, N., Riddell, D. J., Robinson, K., & Geobey, S. (2014). Five configurations for scaling up social innovation: Case examples of nonprofit organizations from Canada. The Journal of

Applied Behavioral Science, 50(3), 234-260.
Wolde, Z., Wei, W., Kunpeng, W. and Ketema, H., 2020. Local community perceptions toward livelihood and water–energy–food nexus: A perspective on food security. Food and Energy Security, p.207.
WWF 2017. The Food-Energy-Nexus as a lens for delivering the UN's Sustainable Development Goals in Southern Africa. Cape Town, South Africa: World Wide Fund for Nature.
YILLIA, P. T. 2016. Water-Energy-Food nexus: framing the opportunities, challenges and synergies for implementing the SDGs. Österreichische Wasser-und Abfallwirtschaft, 68, 86-98
Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: Concepts, questions and methodologies. J. Clean. Prod. 195, 625–639. doi:10.1016/j.jclepro.2018.05.194
Zwane, M and Montmasson-Clair, G. 2016. Climate Change Adaptation and Agriculture in South Africa: A Policy Assessment. WWF-SA, World Wide Fund South Africa, Cape Town, South Africa

APPENDIX 1: WEF NEXUS MASTER CLASS

Online session: June 13-15, 2022 from 10am-1pm each day

Day		**Topic**	**Content/Objective**	**Proposed Format**	**Lead Facilitator**	**Approx. timing**	**Material**
0	0:1	Preparatory materials Introduction to nexus thinking and analysis	Overview of WEF Nexus concepts. Introduction to systems thinking and analysis.	*Preparatory material* WEF Nexus background materials: -overview and concepts -nexus thinking and system analysis -nexus indicators -Hoff Framework -conceptual mapping -causal loop diagrams -systems dynamics modelling	University of KwaZulu-Natal IHE Delft Penn State WRC GWP-SA IWMI		PPT slides/Short videos Existing WEF videos (online material) Links to online material. Recent papers
1	1:1	Introduction to nexus thinking: *Lecture; Q&A*	Introduction to the course. • Welcome • Purpose	Introduction and experiences from participants and	UKZN/IHE	30 mins	Material shared in 0:1

Day		Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
			• Structure and Approach	facilitation team.			
	1:2	Introduction to indicators. Overview of WEF nexus index and iWEF tool *Lecture; Group work*	Introduce indicators and the link to achieving SDGs, sustainable food systems and a circular economy	Lecture followed by group exercise and discussion.	JWET/UKZN	1.5	
	1:3	Introduction to indicators: *Feedback and discussion on the group work*		Group discussions with feedback	JWET/UKZN	1	
2	2:1	Introduction to mapping WEF nexus relationships and feedback: *Lecture; Q&A*	Introduce participants to the Hoff framework, conceptual mapping, causal loop diagrams, and SDM method and application.	Lecture followed by group work and discussion.	IHE Delft; UKZN	60 mins	Material shared in 0:1
	2:2	Introduction to mapping WEF nexus relationships and feedback: *Group work*		Guided class exercise. Fill in the revised Hoff framework2 to describe a WEF Nexus case study. Template and literature provided	IHE Delft; UKZN	1.5	Material shared in 0:2
	2:3	Introduction to mapping WEF nexus relationships and feedback:		Group discussions with feedback	IHE Delft; UKZN	1	

Day		Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
		Feedback and discussion on the group work					
3	3:1	WEF Nexus discourse in southern Africa and financing WEF nexus investments *Lecture; Q&A*	To learn how the WEF nexus can be used to inform investment planning	Lectures followed by group work and discussion	GWP-SA	30 mins	Knowledge from experienced policy makers. Videos.
	3:2	WEF Nexus discourse in southern Africa and financing WEF nexus investments *Group work*		Group work	GWP-SA	1	
	3:3	WEF Nexus discourse in southern Africa and financing WEF nexus investments *Feedback and discussion on the group work*		Group discussions with feedback	GWP-SA	30 mins	
	3:4	Wrap-Up and closure			JWET; IHE Delft, UKZN; GWP-SA; WRC; Penn State	30 mins	

APPENDIX 2: PROPOSED TOPIC, FORMAT AND LEAD FACILITATORS FOR THE WEF NEXUS WINTER SCHOOL.

	Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
0:1	Introduction to nexus thinking Introduction to WEF nexus frameworks, tools, and indicators	To provide background and introduction to the concept of nexus thinking and how it has emerged, as well as various other nexus that exist. Introduction to systems analysis, thinking and representation To provide background about current theory and practice related to WEF nexus frameworks, tools and indicators and linking them to achieving SDGs, sustainable food systems and a circular economy.	Preparatory material WEF Nexus background materials: -overview and concepts -nexus thinking and system analysis -nexus indicators -Hoff Framework -conceptual mapping -causal loop diagrams -systems dynamics modelling	UKZN IHE Delft Penn State WRC GWP	4-6 hrs depending on detail.	PPT slides/Short videos Existing WEF videos (online material) Papers/books Links to online material.
0:2	Homework Exercise *The homework has to be sent to XXX by July 24th. *The relevant material collected to	Participants fill in the revised Hoff framework[2] to describe a WEF Nexus case study.	-Hoff Framework table	IHE Delft University of KwaZulu-Natal		Hoff et al., 2019[2] paper

	Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
	fill in the Hoff framework needs to be brought for Day 2 class Exercise: develop a framework for their own country following the analytical framework suggested by Hoff et al., 2019[2] Individual exercise					
1:1	Identify indicators that are applicable for tracking WEF security and SDGs achievement *Recap lecture; Q&A; Group work and discussion*	Participants explore and analyse the WEF Nexus Index for their own country.	Recap lecture, group exercise and discussions. Group exercise and group discussions.	IHE-Delft, JWET, UKZN	Half day	Lectures. Study notes and exercise guidelines. Worked examples. WEF nexus index exercise
1:2	*Group work*	Participants explore the iWEF tool	Group exercise. Explore the iWEF tool Compare and contrast global vs local level tool and appropriate indicators.	IHE-Delft, JWET, UKZN	Half day	Study notes and exercise guidelines. iWEF tool structured exercise
2:1	Develop a WEF nexus conceptual map/s	Participants apply a high-level nexus mapping	Recap lecture and practical exercise.	IHE-Delft & University of KwaZulu-Natal	All day	Lectures. Study notes and exercise guidelines.

	Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
	Recap lecture; Q&A; individual exercise and discussion	with the case study assessed in the Hoff Framework filled in as a homework.	Individual exercise. Develop conceptual map/s of the case study described by using the Hoff framework developed as homework before the Masterclass Present back to plenary and feedback session			Worked examples.
2:2	Excursion preparation	Shares logistics and field notes. Tis and pointers.				
3	Day 3 Observing the WEF nexus in practice.	To expose participants to a real life WEF interlinkages and how the WEF nexus can be applied to informing solutions to real life challenges	Excursion to show and explore WEF nexus relationships in real life setting. Participants to use this to further apply knowledge gained in course to date.	Water Research Commission & Department of Water & Sanitation	Full Day	Field trip description. Study sheet and exercise guidelines.
4:1	Day 4 Session 1 Introduction to WEF nexus Serious Game *Lecture; Q&A*	Introduce the development of WEF nexus serious games and the case studies to which they are applied. Briefly demonstrate the game	Lecture and short game demonstration.	IHE Delft	Half Day	Lecture, online demo

	Topic	Content/Objective	Proposed Format	Lead Facilitator	Approx. timing	Material
		essentials.				
4:2	Day 4 Session 2 Serious game playing *Group work and discussion*	In small groups, choose a playable nexus case study, and play the serious game using structured questions to answer about the nexus.	Practical group-based gaming session Present back to plenary and feedback session	IHE Delft	Half Day	Structured gaming session
5:1	Day 5 Session 1 WEF Nexus discourse in southern Africa and Governance framework	To learn how the WEF nexus can be used to facilitate multi-partner and multi-level discourse	Group work and feedback Lectures	Global Water Partnership – Southern Africa	Half day	Shared knowledge from experienced policy makers. Videos.
5:2	Day 5 Session 2	Wrap-Up and closure			1 hour	

APPENDIX 3: INTRODUCTORY WEF NEXUS SHORT COURSE

1	COURSE TITLE
	• Water Energy Food Nexus as a Sustainable Resource Management Tool – Local Scale Applications
2	COURSE OBJECTIVE
	• To equip trainees with the requisite understanding and skills to apply the WEF nexus approach for natural resources management to ensure resource securities for the target population
3	LEARNING OUTCOMES
	At the end of the short course, the trainees will be able to: • Define the WEF nexus and its relevant variants • Understand the scope of application of the WEF nexus from technical to policy aspects. • Define the spatial scale of applying the WEF nexus • Define the temporal scale of application of the WEF nexus • Define and identify the data requirements for use in the WEF nexus • Identify and select the appropriate WEF nexus models/software and applicable techniques • Apply the WEF nexus to specific local scales
4	TARGET TRAINEES
	• Researchers, technical officers, project implementers, policy people
5	COURSE DURATION
	• 4 days
6	COURSE DETAILS
	Day 1 • Introduction to the WEF nexus concept – the W.W.W.H.W. of the WEF nexus • WEF nexus variants • WEF nexus scope of application with relevant examples from around the world • Spatial scale issues when applying the WEF nexus • Temporal scale issues in applying the WEF nexus Day 2 • WEF nexus indicators and their applicability and usability • Data issues for the WEF nexus • Data sources and actual sourcing for the WEF nexus • Data quality and data cleaning for the WEF nexus • WEF nexus models/source and other WEF nexus methodologies Day 3 • Group practical – WEF nexus problem definition and set up • Group practical – WEF nexus practical problem solving Day 4 • Group practical – WEF nexus assignment presentation and feedback to groups
7	TEACHING & LEARNING METHODS
	• Interactive lectures from WEF nexus experts • Individual trainee tasks with feedback, e.g. problem definition, problem scoping, model selection • Interactive practicals with WEF nexus experts and the trainees • Individual trainee hands on practical tasks on specific aspects, e.g. data sourcing, data cleaning, data input into WEF nexus models • Group hands on tasks on natural resources management applying the WEF nexus approach for specific defined problem cases – from the beginning to the end

	• Group feedback with critiquing and assessment to the class
8	LEARNING ASSESSMENT
	Learning outcomes will be assessed through: • Summative assessment of the theoretical aspects of the WEF nexus • Assessment of the practical project on application of the WEF nexus
9	REFERENCE MATERIALS
	1) FAO (2014): The Water-Energy-Food Nexus. A New Approach in Support of Food Security and Sustainable Agriculture.

APPENDIX 4 PUBLICATIONS AND CONFERENCE PRESENTATIONS

Publications

Dlamini N, Senzanje A, and Mabhaudhi T. (2023). Assessing Climate Change Impacts on Surface Water Availability using the WEAP Model: A Case Study of the Buffalo River Catchment, South Africa. Journal of Hydrology: Regional Studies (Published Manuscript – https://doi.org/10.1016/j.ejrh.2023.101330

Dlamini N, Senzanje A, and Mabhaudhi T. (2023). Modelling the Water Supply-Demand Relationship in the Buffalo River Catchment, South Africa, Under Climate Change. PLOSClimate. (Manuscript Under Review)

Conference Presentations

Dlamini N, Senzanje A, and Mabhaudhi T. Assessing Climate Change Impacts on Surface Water Availability using the WEAP Model: A Case Study of the Buffalo River Catchment, South Africa. *University of KwaZulu-Natal – College of Agriculture, Engineering and Science Postgraduate Research and Innovation Symposium (PRIS). 8 December 2022. Oral Presentation Under: School of Engineering. Online*.

Dlamini N, Senzanje A, and Mabhaudhi T. Assessing Climate Change Impacts on Surface Water Availability using the WEAP Model: A Case Study of the Buffalo River Catchment, South Africa. *24th International Commission on Irrigation and Drainage (ICID) Meeting. 5 October 2022. Oral Presentation Under Special Session: Developing the Future Tools for Managing Uncertainty in Irrigation Water Supply – System Modelling. Adelaide, Australia*.

Dlamini N, Senzanje A, and Mabhaudhi T. Assessing Climate Change Impacts on Surface Water Availability using the WEAP Model: A Case Study of the Buffalo River Catchment, South Africa. *Kenya Society of Environmental Biological and Agricultural Engineers (KeSEBAE) Virtual Annual Conference 2021. 25 November 2021. Oral Presentation Under Special Session: Engineering for Transformation. Online.*

Kaula A., Mudhara M., and Senzanje A. Water-Energy-Food Nexus: Trade-offs in the use of water and energy for food production among small holder farmers in KwaZulu-Natal Province, South Africa. *Paper presented at the 23rd WaterNet/WARFSA/GWP-SA symposium, 19 October 2022, Sun City, South Africa*.

Kaula A., Mudhara M., and Senzanje A. Water-Energy-Food Nexus: Trade-offs in WEF resources for food and nutrition security among smallholder irrigation farmers in KwaZulu-Natal Province, South Africa. *Paper presented at the University of KwaZulu-Natal – College of Agriculture, Engineering and Science, Postgraduate Research and Innovation Symposium (PRIS) 2022, 9 December 2022. Online*

Kaula A., Mudhara M., and Senzanje A. Water-Energy-Food Nexus: Trade-offs in WEF resources for food and nutrition security among smallholder irrigation farmers in KwaZulu-Natal Province, South Africa. *Oral Presentation, The South African National Committee on Irrigation & Drainage (SANCID) symposium 2023. Tzaneen, South Africa*

APPENDIX 5: MSC DISSERTATIONS

Student: Miss Nosipho Dlamini (MSc Engineering)

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

Abstract:

South Africa's climate has high spatial and temporal variability. Literature on historical rainfall patterns shows substantial declines in rainfall across the country, except in south-western South Africa, which displays increasing trends. Under the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios, statistically downscaled rainfall projections show different patterns across South Africa throughout the 21st century. Literature indicates that this uncertainty will majorly impact South Africa's surface water availability as its main input variable is rainfall; hence, all possible outcomes need to be planned for. Planning should include the energy and food production sectors as they primarily depend on the water sector. The Buffalo River catchment, situated in the northern parts of KwaZulu-Natal, South Africa, is a high rainfall receiving area, with a mean annual precipitation of 802 mm. Despite its abundant rainfall, the catchment has had its fair share of droughts, significantly impacting livelihoods and socio-economic activities. Recent reports indicate that the Buffalo River catchment's surface water storage facilities are insufficient to meet the population's demands by 2050. A detailed water resources assessment is required to confirm and quantify the possible alterations that climate change could cause to the catchment's hydrology before any actions can be taken, especially regarding increasing the water storage capacity of the catchment.

As such, this study aims to investigate and assess the impacts of climate change on the Buffalo River catchment's surface water availability and reliability of water resources in meeting projected water demands, with a specific focus on agricultural and energy generation water demands. Furthermore, the study aims to develop integrated water resources adaptation strategies to increase water, energy and food security within the catchment.

Due to its transdisciplinary nature, the Water-Energy-Food (WEF) nexus methodology was used as an analytical tool to carry out the research's objectives. The study was based on the null hypotheses of climate change not varying surface water availability and reliability, and that the optimized CC water management strategies will not yield any improvements in merging potential gaps between water supply and demands.

Study findings indicate that the Buffalo River catchment is anticipated to receive increases in precipitation magnitude and fluctuations throughout the 21st century. However, the increases in

surface water availability that result from the anticipated rainfall increases are insufficient and unreliable to meet the rise in demands for water within the catchment, more so the irrigation demands. Through investigating the catchment's already-existing proposed climate change policy interventions for water resources management, the study found that they were centred around boosting domestic water provisions whilst only meeting <3% of projected demands by the energy and agricultural sector. As such, by optimizing these policy plans using the WEF nexus' Climate, Land-Use and Water Strategies (CLEWS) framework's analytical tools, integrated climate change adaptation strategies were formulated, which were modelled to significantly improve the water storage capacity of the catchment, as well as water allocations and distribution among water users.

The study concluded that the Buffalo River catchment's surface water availability is expected to increase under climate change, however, current water storage capacity is not reliable to meet water demands throughout the 21st century. Lastly, the study also concluded that the catchment does possess immense potential for improved surface water availability to merge the gap between its water supplies and demands. Thus, the null hypotheses stipulated in this research are rejected. For discussions, policymaking and general research related to these improvements in water resources management in the Buffalo River catchment, the climate change adaptation strategies established in this research are recommended. Also, based on model evaluation statistics, the WEF nexus was successful in examining the interrelations among WEF resources, and is recommended for future studies to examine long-term integrated demand-supply strategies for WEF sectors.

Student: Miss Aphiwe Kaula (MSc Agricultural Economics)

Title: Water Energy Food Nexus: Trade-offs in the use of water and energy for food and nutrition security among smallholder farmers in KwaZulu-Natal

Abstract:

Resource-intensive farming systems, which have caused water scarcity and significant deforestation, cannot deliver sustainable agricultural production and food. Resource-intensive farming systems, which have caused water scarcity and significant deforestation, cannot provide sustainable agricultural production and nutrition. Resource-intensive farming negatively affects the Water-Energy-Food nexus through inefficient management of resources, which is caused by not looking at appropriate nexus mixes that ensure optimal resource use. The resources must be balanced by acknowledging that water, energy and food are unique regarding behaviours, properties, nature and cycles. The balance between the three components needs sustainable, efficient management and awareness to assure effective synergy and assist in resource security and productivity. This study aimed to contribute to the literature in two ways. The first objective of this study is to investigate the trade-offs between water, energy and food in smallholder farming systems. Secondly, the study sought to examine the contribution of WEF resources in determining household-level food and nutrition security. A structured questionnaire was administered to 345 randomly selected smallholder irrigators in Jozini, Mpofana and Msinga local municipalities, KwaZulu-Natal, South Africa. Data were captured and analysed through the Statistical Package for Social Sciences (SPSS) version 26 to run the Cobb-Douglas production function. Cobb-Douglas production function examined how water and energy resources affect food production. STATA version 17 was used to run the Tobit model to determine the WEF contribution to household food and nutrition security.

The results illustrated a synergy between the gross revenue and the WEF resources. The Cobb-Douglas production function results revealed that factors such as marital status, Household monthly income, minutes it takes to fetch water, no access to electricity, energy input costs for plots, and index of synergy for the size of cultivated irrigated fields and energy input costs determine the food output produced in the study area.

The data collected was analysed using the Tobit regression. The econometric results indicated that having water taps in dwellings as the primary water source increases household food and nutrition security. This implies that the availability and accessibility of water for household use are crucial. Furthermore, the empirical results indicated that four other statistically significant variables positively influenced food and nutrition security. The four variables were monthly income, cost of energy for household use, food expenditure and cost of energy per hectare for food production. The study concluded that water resources are not widely available and accessible to smallholder farmers. Strategies and policy interventions should focus on overcoming difficulties affecting the availability and accessibility of WEF resources whilst prioritising that farmers are aware of managing scarce resources.

APPENDIX 6: POTENTIAL WEF NEXUS STAKEHOLDERS IN SOUTH AFRICA.

Name	Organisation	Contact details
Gerhard Backeberg	WRC	gerhardb@wrc.org.za
Sylvester Mpandeli	WRC	Sylvesterm@wrc.org.za
Luxon Nhamo	IWMI-SA	l.nhamo@cgiar.org
Albert T. Modi	School of Agricultural, Earth and Environmental Sciences, UKZN	modiat@ukzn.ac.za
Amos Madhlopa	ERC, UCT	Amos.madhlopa@uct.ac.za
Graham Jewitt	CWRR, UKZN	JewittG@ukzn.ac.za
Tafadzwanashe Mabhaudhi	SAEES, UKZN	tmabhaudhi@gmail.com; mabhaudhi@ukzn.ac.za
Emma Archer van Garderen	CSIR, Natural Resources and the Environment	earcher@csir.co.za
Willem Landman	CSIR, Natural Resources and the Environment	willem.landman@up.ac.za
Manisha Gulati	WWF-SA	mgulati@wwf.org.za
Inga Jacobs-Mata	CSIR	ijacobsmata@csir.co.za
Andre Jooste	National Agricultural Marketing Council	
Dhesigen Naidoo	ERC	dhesn@wrc.org.za
Salim Fakir	WWF-SA	
Suzanne Carter	WWF-SA	
Gisela Prasad	ERC, UCT	Gisela.prasad@uct.ac.za
Adrian Stone	ERC, UCT	adrian.stone@uct.ac.za
Alison Hughes	ERC, UCT	alison.hughes@uct.ac.za
Theodor Stewart	Department of Statistical Sciences, UCT	Theodor.Stewart@uct.ac.za
Sumayya Goga	Pegasys Institute	
Guy Pegram	Pegasys Institute	guy@pegasys.co.za
Adams Shafick	WRC	shaficka@wrc.org.za
Ahjum Fadiel	ERC, UCT	mf.ahjum@uct.ac.za
Joseph Baloyi	Department of Animal Science, University of Venda	Joseph.baloyi@univen.ac.za
Ruth Beukman	GWP-SA	r.beukman@cgiar.org
Chris Buckley	Pollution Research Group, UKZN	buckley@ukzn.ac.za
Mapambe Intelligent Chauke	South African Local Government Association (SALGA)	ichauke@salga.org.za
Joyce Chitja	African Centre for Food Security, UKZN	Chitjaj@ukzn.ac.za
Cobus Botha	ARC	Bothac@arc.agric.za

Name	Organisation	Contact details
Christine Colvin	Freshwater Programme, WWF-SA	ccolvin@wwf.org.za
Chris Dickens	IWMI-SA	c.dickens@cgiar.org
Nico Elema	Stellenbosch University	nicoelema@sun.ac.za
Terry Everson	School of Life Sciences, UKZN	eversonT@ukzn.ac.za
Mary Jean Gabriel	DAFF	MaryJeanG@daff.gov.za
Steve Gilham	Umgeni Water	steve.gillham@umgeni.co.za
Martin Ginster	SASOL	martin.ginster@sasol.com
Mark Gush	Natural Resources & Environment, CSIR	MGush@csir.co.za
Mzukisi Gwata	City of Johannesburg	mzukisig@joburg.org.za
Riaz Hamid	South African National Energy Development Institute (SANEDI)	riazh@sanedi.org.za
Nomthandazo Hanise	Buffalo City Metropolitan Municipality	TandiH@buffalocity.gov.za
Nebo Jovanovic	CSIR	njovanovic@csir.co.za
Khavhagali Vhalinavho	DEA	vkhavhagali@environment.gov.za
Thabhiso Koatla	Institute for Soil, Climate and Water, ARC	KoatlaT@arc.agric.za
Richard Kunz	Department of Hydrology, UKZN	KunzR@ukzn.ac.za
Jørgen Erik Larsen	Strategic Sector Cooperation Team, Embassy of Denmark	joelar@um.dk
Lesoli Mota	Fort Cox College of Agriculture and Forestry	lesoli@fortcox.ac.za
Stanley Liphadzi	WRC	stanleyl@wrc.org.za
Heila Lotz-Sisitka	Environmental Learning Research Centre, Rhodes University	h.lotz@ru.ac.za
Madikizela Bonani	WRC	agnesm@wrc.org.za
Zamile Madyibi	Department of Rural Development and Agrarian Reform, Province of the Eastern Cape	Zamile.madyibi@drdar.gov.za
Lulekwa Makapela	CSIR	LMakapela@csir.co.za
Sampson Mamphweli	Institute of Technology, University of Fort Hare	smamphweli@ufh.ac.za
Everisto Mapedza	IWMI	E.Mapedza@cgiar.org

Name	Organisation	Contact details
Kgoroshi William Mashabane	Department of Rural Development and Land Reform, Republic of South Africa	kwmashabane@ruraldevelopment.gov.za
Cecil Masoka	Department of Science and Technology, Republic of South Africa	cecil.masoka@dst.gov.za
Mercedes Mathebula	City of Tshwane	mercedesM@tshwane.gov.za
Leluma Matooane	Department of Science and Technology, Republic of South Africa	Leluma.Matooane@dst.gov.za
Samukelisiwe Mdlalose	Mogale City Local Municipality	samukelisiwe.mdlalose@mogalecity.gov.za
Nadine Methner	ACDI, UCT	Nadine.methner@uct.ac.za
Smangele Mgquba	DWS	mgqubas@dwa.gov.za
Enoch Mhlanga	Department of Rural Development and Land Reform, Republic of South Africa	MEMhlanga@ruraldevelopment.gov.za
Stephanie Midgley	ACDI, UCT	Stephanie.midgley@gmail.com
Nomvuzo Mjadu	DAFF	
Muzi Mkhize	DoE	Muzi.Mkhize@energy.gov.za
Mokhele Moeletsi	ARC	moeletsim@arc.agric.za
Puleng Mofokeng	DAFF	Pulengm@daff.gov.za
Nomakhaya Monde	Faculty of Science and Agriculture, University of Fort Hare	nmonde@ufh.ac.za
Motlole Christopher Moseki	WRC	MosekiC@dwa.gov.za
Andrew Motha	DEA	AMotha@environment.gov.za
Lwandle Mqadi	Eskom	MqadiL@eskom.co.za
Mandla Msibi	WRC	mandlam@wrc.org.za
Shonisani Munzhedzi	DEA	SMunzhedzi@environment.gov.za
Valerie Naidoo	WRC	Valerien@wrc.org.za
Mark New	ACDI, UCT	Mark.new@uct.ac.za
Wandile Nomquphu	WRC	wandilen@wrc.org.za
Bongani (Lucky) Ntshangase	South African Weather Service	lucky.ntsangwane@weathersa.co.za
Jane Olwoch	Earth Observation, South African National Space Agency	jolwoch@sansa.org.za
Nic Opperman	Agri SA	Nic@agrisa.co.za

Name	Organisation	Contact details
Brilliant Petja	WRC	Brilliantp@wrc.org.za
Faith Phooko	DEA	FPhooko@environment.gov.za
Harrison Pienaar	CSIR	hpienaar@csir.co.za
Nomawethu Qase	DoE	Noma.Qase@energy.gov.za
Suvritha Ramphal	Embassy of Denmark	suvram@um.dk
Tshilidzi Ramuedzisi	DMR	tshilidzi.ramuedzisi@energy.gov.za
Rendani Ramugondo	Department of Agriculture and Rural Development, Province of Limpopo	ramugondorr@agric.limpopo.gov.za
Imraan Saloojee	Department of Science and Technology, Republic of South Africa	imraan.saloojee@dst.gov.za
Aidan Senzanje	Department of Bioresources (Agricultural) Engineering, UKZN	senzanjea@ukzn.ac.za
Roland Schulze	Department of Hydrology, UKZN	SchulzeR@ukzn.ac.za
Pulane Miriam Sebothoma	ARC	pulane@arc.agric.za
Moddy Sethusha	National Disaster Management Centre, Department of Cooperative Governance, Republic of South Africa	ModdyS@ndmc.gov.za
Indhul Sherman	Transnet	sherman.indhul@transnet.net
Lindiwe Majele Sibanda	Food, Agriculture and Natural Resources Policy Analysis Network	lmsibanda@fanrpan.org
Abraham Singels	South African Sugarcane Research Institute	Abraham.Singels@sugar.org.za
Michael Smith	Department of Economics and Finance, UKZN	mikesmith@live.co.za
Sabine Stuart-Hill	Centre for Water Resources Research, UKZN	Stuart-Hills@ukzn.ac.za
Gareth Simpson	Jones & Wagener	simpson@jaws.co.za
Andrew Takawira	GWP-SA	A.Takawira@cgiar.org
Rina Taviv	Department of Agriculture and Rural Development, Province of Gauteng	Rina.Taviv@gauteng.gov.za
David Tinarwo	Department of Physics, University of Venda	David.tinarwo@univen.ac.za

Name	Organisation	Contact details
Rabelani Tshikalanke	DEA	RTshikalanke@environment.gov.za
Kathu Tshikolomo	Department of Agriculture and Rural Development, Province of Limpopo	Tshikolomo@gmail.com
Susan Viljoen	Upper Umgeni, WWF-SA	sviljoen@wwf.org.za
Karen Villholth	IWMI	k.villholth@cgiar.org
Katharine Vincent	Kulima Integrated Development Solutions	katharine@kulima.com
Tatjana von Bormann	WWF-SA	tvbormann@wwf.org.za
Jessica Wilson	Environmental Monitoring Group	jessica@emg.org.za
Harald Winkler	ERC, UCT	harald.winkler@uct.ac.za
Khanyiso Zihlangu	DoE	khanyiso.zihlangu@energy.gov.za
Angelinus Franke	Faculty of Natural and Agricultural Sciences, UFS	FrankeAC@ufs.ac.za
Leocadia Zhou	Faculty of Science & Agriculture – Risk & Vulnerability Assessment Centre, University of Fort Hare	LZhou@ufh.ac.za
Olusola Ololade	Centre for Environmental Management, UFS	shola.ololade@gmail.com