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

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Water, energy and food are considered the main resources that sustain life. In this regard, they are essential to socio-economic development at national-, regional- and global scales. These three resources are interlinked in various ways – such interconnections and inter-dependencies are often described by the famous Water-Food-Energy (WEF) nexus paradigm. The WEF nexus concept emerged in the international community, in part, in response to the climate change and social changes, e.g. population growth, globalization, economic growth, urbanisation, growing inequalities, and social discontent, which are exacerbating the growing demand for already scarce and strained resources. Consequently, decision-makers in the water-, energy- and food security sectors are continuously faced with an enormous of accounting for the synergies, tensions and potential trade-offs between the resources at various spatial and temporal scales as well as potential transboundary resource-related conflicts. There is no doubt that the WEF nexus offers a promising framework capable of, e.g. dealing with trade-offs, synergies among the three resource systems, social and environmental impacts, as well as supporting the development of cross-sectorial policies. In addition, it has been widely accepted that the WEF resources play a significant role, particularly towards the attainment of the 2030 Agenda for Sustainable Development Goals (SDGs). Notwithstanding the inherent major potential, the growing WEF nexus body of knowledge is yet to be adequately translated from theory to practice.

As the WEF resources are continuously under pressure (due to economic and population growth, rapid urbanisation, land degradation, changing diets, and unplanned consumption, etc.), the implementation of SDGs on themes and issues relating to food security, good health and wellbeing, as well as affordable energy, is likely to be impacted. Consequently, there is a consensus among scientists, governments, and policymakers on the necessity to address the compounding challenges, including an understanding of the WEF nexus and the accompanying trade-offs as well as the translation of the WEF nexus framework from theory to practice. It is against this background that, the Water Research Commission (WRC) project number C2019/2020-00020, titled "*From theory to practice: Developing a case study and guidelines for Water-Energy-Food (WEF) nexus implementation in Africa*" was contracted to and executed by the South African Weather Service (SAWS) and the Kenya Water Institute (KEWI), in collaboration with the University of KwaZulu-Natal and the Central University of Technology (CUT). In particular, the project aimed to develop a robust nexus modelling methodology that could be realised in the form of a smart decision tool that is applicable and in support of the cross-sectoral complexity of the WEF resources in Eastern (Narok County, Kenya) and Southern (Vhembe District Municipality, South Africa) Africa under changing climate. The specific objectives of the project were to: a) conduct a situational analysis of the WEF nexus across the African continent with particular emphasis on Southern and Eastern Africa; b) develop an applicable and scalable WEF nexus modelling approach for the region that can be replicated at national, basin or regional levels; c) apply the model and framework to assess rural livelihoods, health, and wellbeing at local level; d) apply the WEF nexus model for scenario planning and to assess SDG performance at local level; and e) to apply the WEF nexus model for scenario planning and to assess (and highlight opportunities for linking to) SDGs.

The project objectives were achieved using desktop research, and the Integrative WEF Nexus Analytical (iWEF) tool to assess the linkages among the WEF resources and rural livelihoods, health, and well-being as well as the linkages with the relevant SDGs in the two study sites. Community and expert surveys were also used to validate the literature and model results. The iWEF tool is based on the six WEF nexus indicators described in Nhamo et al. (2020a). The WEF nexus indicators include the availability and productivity of water resources; accessibility and productivity of energy resources; and self-sufficiency and productivity of food resources. The same indicators were also used for the expert and community surveys. The key findings of the project are summarised as follows:

- While the field of WEF nexus research has greatly expanded globally, it is still underdeveloped in Africa, as shown by a literature review study based on a bibliometric analysis of WEF nexus scientific articles published between 2000 and 2020. Nonetheless, scientific publications' growth observed from 2017 to 2020 suggested that research on the WEF nexus has been gaining traction in Africa and is likely to gradually grow in the coming years. The exploration of the mutual benefits of the WEF-WEFE (Water, Energy, Food, and Ecosystems) nexus and hydropower emerged as one of the key themes within the WEF nexus research. This theme is vital given that, most of the hydropower projects (HPPs) often generate various cross-border and cross-sector inter-dependencies that can be related to water, energy and food security. Overall, the review study contributed towards efforts to build a theoretical framework upon which the WEF nexus theory could be translated into practice, in support of its implementation.
- The iWEF nexus analytical model was applied to evaluate interlinkages among variables in the WEF system in Vhembe District Municipality and Narok County. The results derived from the integrated composite index and spider diagram demonstrated that the management of resources is marginally sustainable in both study sites. The results contribute towards the achievement of SDGs and support decision-making including effective use, allocation, and management thereof of water, energy and food resources at a local level. In the assessment of sustainable livelihoods, health and wellbeing indicators, the results show that the resources for a sustainable livelihood in Vhembe District Municipality are more sustainable than those in Narok County.

- A framework for WEF nexus scenario planning was developed to assist the Vhembe District Municipality and Narok County in decision-making on water, energy and food economic sectors. The study first involved conducting a review study to appraise the linkages between SDGs and WEF as well as formulate and test the interconnections between WEFE pillars and SDGs, using three case studies in South Africa. Secondly, a scenario canvas/exploratory scenario storylines were used to determine the plausible futures from the perspective of sustainability and WEF resource management while considering: 1) societal development options, 2) environmental changes, 3) socio-economic and political changes, and 4) technological changes. Lastly, a WEF modelling framework comprising a "scenario canvas module" at the WEF resources security index level is recommended as a future research endeavour.
- Recommendations for the implementation of the WEF nexus approach at the subnational level using the case study of the Vhembe District Municipality and Narok County were provided. These recommendations take into account existing WEF nexus vulnerabilities and possible challenges for such implementation within the two study sites.

In general, the literature review highlighted that in Africa, six main WEF themes have been the foci of research including WEF linkages to water resources, water supply, resource management, decision making and climate change as well as some emerging themes. Several issues constrain the mainstreaming or achievement of trade-offs, compromises, or synergies in the resolution of the competition between the nexus elements. The key nexus issues for southern Africa include cross-sectoral policy linkages among WEF sectors, the impact of climate change on WEF resources, at local and regional levels, irrigated agriculture from the WEF perspective, coordinated action through sector policies and cross-sectoral linkages, analysis of interlinkages between charcoal, livestock, and hydrological processes. The interlinkages among variables relating to the WEF resources in the two sites were evaluated using the iWEF nexus analytical model and the built-in WEF nexus indicators in the model were assessed based on a desktop analytic study and survey questionnaire. The integrated composite indices for Vhembe and Narok suggest that resource management is marginally sustainable in both river basins. Furthermore, the results showed evidence of imbalanced resource management across the river basins and the outcomes of the assessments can help inform policy interventions related to the assessment and test the performances of the indicators against the relevant policies for both Kenya and South Africa. Factors such as population growth as well as rapid and unplanned urbanisation were identified as having a huge impact on the nexus components and consequently also affecting the livelihoods, health and wellbeing of the communities in both Vhembe and Narok. The project also included WEF nexus scenario planning to understand the future impacts of WEF resources and support planning and decision-making in the study sites.

The project recognised the need to address issues identified in literature such as institutional and policy silos; national and development partner institutional arrangements that do not favour systems thinking; limited technical capacity; rigid development plans as well as dynamic power relationships between national institutions and transboundary actors who may have different interests. It was further recommended that key actors at the local level be capacitated to comprehend and integrate the nexus approach at local level operations and decision-making (e.g. budget allocation in municipal planning documents and enforcement of by-laws). Also, national and regional legislation and agreements signed to manage transboundary policies developed need to be implemented and enforced by all actors to ensure tangible change is realized. Furthermore, the methods and frameworks need to encompass both quantitative and qualitative information at multiple scales including aspects such as gender, policy development and adoption among others. Several recommendations for future research and interventions for the WEF implementation at the subnational level were put forward including facilitating mechanisms that promote private sector funding for WEF research and projects at the subnational level; creating an enabling research-policy-practice environment to ensure the uptake of science recommendations to support sustainable utilisation and management of nexus resources particularly given the emergent risks associated with pandemics, political unrest, and global change; research studies can adopt the county level (Kenya) or district development model (South Africa) to enhance community involvement in co-designing socially inclusive actions to sustain the WEF and linked resources in different contexts.

Capacity building and knowledge transfer activities included scientific training of students for postgraduate qualifications, published scientific paper, and stakeholder engagement workshops (APPENDIX 3). Capacity building also included the development of the SAWS project team members on different aspects of the projects including the use of the iWEF Tool and scenario planning.

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ACRONYMS & ABBREVIATIONS

AHP	Analytic Hierarchy Process
CCTE	Communication, Collaboration, Trust and Empowerment
CR	Consistence Ratio
CSIR	Council for Scientific and Industrial Research
CUT	Central University of Technology
DRC	Democratic Republic of the Congo
DSS	Decision Support System
IFPRI	International Food Policy Research Institute
IRRI	International Rice Research Institute
ITCZ	Inter-Tropical Convergence Zone
iWEF	integrated Water-Energy-Food
IWMI	International Water Management Institute
KEWI	Kenya Water Institute
KNP	Kruger National Park
K-WEFS	Karawang WEF security
LRB	Limpopo River Basin
MCA	Multiple Correspondence Analysis
MCDM	Multi-Criteria Decision-Making
MCP	Multiple Country Publications
MFCB	Mau Forest Catchment Basin
MRB	Mara River Basin
MTDF	Makuya Tshikondeni Development Foundation
NBA	Niger Basin Authority

NDCs	Nationally Determined Contributions
NRM	Natural Resource Management
PCM	Pairwise Comparison Matrix
RBRs	Resourced-Based Regions’
SAWS	South African Weather Service
SCP	Single Country Publications
SDGs	Sustainable Development Goals
SNP	Serengeti National Park
UKZN	University of KwaZulu-Natal
USA	United States of America
VDM	Vhembe District Municipality
WEF	Water-Energy-Food
WEFE	Water, Energy, Food, and Ecosystems
WoS	Web of Science
WRC	Water Research Commission
WRUAs	Water Resources Users Associations

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1. BACKGROUND

1.1. Introduction

There is compelling evidence that water, energy and food (WEF) systems are inextricably intertwined, implying that actions in one resource influence the others. The three resources are increasingly under pressure due to various factors such as climate change, population growth, rapid urbanisation, land degradation, unsustainable consumption of resources as well as frequent occurrences of natural hazards such as droughts, and floods, with far-reaching consequences on human, social, economic and environmental sustainability. The demand for WEF resources due to anticipated population growth and climate change impacts has triggered many nations to yarn for innovative solutions. The WEF nexus emerged in the international community in response to climate and social changes and has been widely accepted as a valuable concept that can be used to understand the intricate dynamic interlinkages between the WEF resources and thus contributes towards the natural resources' planning and management. Furthermore, the proposed nexus approach enables the identification of trade-offs and synergies of WEF systems, internalizes social and environmental impacts, and contributes to the development of cross-sectoral policies. Consequently, the WEF nexus approach assists to balance different resource user goals and interests as well as maintains the integrity of ecosystems.

Despite the exciting promises that come along with the WEF nexus concept, its implementation at different spatio-temporal scales has been hampered by many challenges. Such challenges are attributed to existing knowledge gaps in understanding WEF resources interlinkages, limited availability of reliable tools and models, the lack of the necessary data to develop and test such technologies as well as the overall value-chain translation of the WEF nexus concept from theory to practice. This project contributes towards building and enhancing WEF nexus body knowledge in support of the implementation of the nexus approach for effective management of WEF systems at a local scale, using case studies in Vhembe District Municipality (VDM), South Africa, and Narok County in Kenya.

1.2. Project Aims

The project aimed to develop a robust nexus modelling methodology that will be realised in the form of a smart decision tool that is applicable and in support of the cross-sectoral complexity of the WEF resources in Eastern and Southern Africa in a changing climate. The following were the specific objectives of the project:

i) Conduct a situational analysis of the WEF nexus across the African continent with particular emphasis on Southern and Eastern Africa.

ii) Develop an applicable and scalable WEF nexus modelling approach for the region that can be replicated at national, basin, or regional levels.
iii) Apply the model and framework to assess rural livelihoods, health and wellbeing at local level.
iv) Apply the WEF nexus model for scenario planning and to assess SDG performance at local level.
v) Apply the WEF nexus model for scenario planning and assess (and highlight opportunities for linking to) SDGs.

To achieve these objectives, two study areas one in the Limpopo River Basin in South Africa, and the other in the Mara catchment in Kenya were identified as case studies to form the basis for the development of guidelines for WEF nexus implementation in Africa.

1.3. Scope and Limitations

The Water-Energy-Food Nexus project was jointly contracted to the South African Weather Service (SAWS), in collaboration with the Kenya Water Institute (KEWI), Central University of Technology (CUT) and the University of KwaZulu-Natal (UKZN). After assessing the scope of the project from the Kenya side, the project team brought onboard the Maasai Mara University and Kenya Meteorological Department to support the execution of the project. The scope of the project was to conduct a situational analysis of the WEF nexus across the African continent with a focus on Southern and Eastern Africa, develop an applicable and scalable WEF nexus modelling approach for the region that can be replicated, apply the model and framework to assess rural livelihoods, health and wellbeing, apply the WEF nexus model for scenario planning and to assess SDG performance, and for scenario planning and to assess related sustainable development goals (SDGs) with a focus on two study sites, one in the Limpopo Valley in South Africa, and the other in the Mara catchment in Kenya.

The project was executed during the unforeseen circumstances caused by the Covid-19 pandemic and this created unprecedented delays in the overall execution of the project. Specific challenges experienced during the execution of the project include:

- Delays in concluding the partnership approval processes between the institutions involved in the project
- Interruptions in physical stakeholder engagements due to both local and international travel restrictions resulting from COVID-19
- Challenges with obtaining data for the Kenya study site hence some deliverables were not fully achieved due to the unavailability of specific data and social-related information.

In this report, each deliverable is reported as a chapter. Thus, the report is structured as follows:

- *Chapter 2 (Deliverable 2*): Literature Review on the State-of-the-Art WEF Nexus Assessment for southern and eastern Africa
- *Chapter 3 (Deliverable 3):* An applicable and scalable WEF nexus model
- *Chapter 4 (Deliverable 4):* Assessment of rural livelihoods, health and wellbeing using the WEF nexus model
- *Chapter 5 (Deliverable 5):* WEF nexus model for scenario planning and assessment of SDG performance
- *Chapter 6 (Deliverable 6):* Recommendations for implementation of the WEF nexus
- *Chapter 7 (Deliverable 7):* Research agenda for funding research and development on WEF nexus
- *Chapter 8:* Conclusions and recommendations

1.4. Project Study Areas

1.4.1. Vhembe District Municipality, South Africa

The Vhembe District Municipality (VDM) was selected as the study site for South Africa. It falls within the Limpopo Water Management Area and forms part of the Limpopo River Basin shared with Botswana, Zimbabwe and Mozambique. To ensure extensive community engagement and project uptake the Masisi, Bende Mutale, Tshipise and Nthlaveni villages as well as the Tshikondeni mining centre were chosen as study sites and these communities participated in the project (see Figure 1).

The district falls within the subtropical climate with a mean annual rainfall of 500 mm between October and March. Temperatures in Vhembe can reach a maximum of up to 40°C and a minimum of 10°C. Vhembe also experiences recurrent floods, fires and droughts, especially in Thulamela and Musina Local Municipality, which are semi-arid (VDM, 2019). These communities are close to the Kruger National Park (KNP) a transfrontier park that falls within the district with the Pafuri and Punda Maria Gates in Musina and Collins Chabane Local Municipalities respectively and the Makuya Park which has been integrated into KNP. A significant proportion of land in Vhembe is communal land and restitution land that has been given back to the communities after successful land claims, e.g. Nthlaveni community. The area also has a high prevalence of malaria hence health aspects will be integrated into the WEF nexus to support communities and initiatives in the area to mitigate the impacts of malaria. Such initiatives include the Laurelle Zamisa Malaria Research Centre which was established as part of the post-mining closure investment by the Makuya Tshikondeni Development Foundation (MTDF) with support from Lumin8.

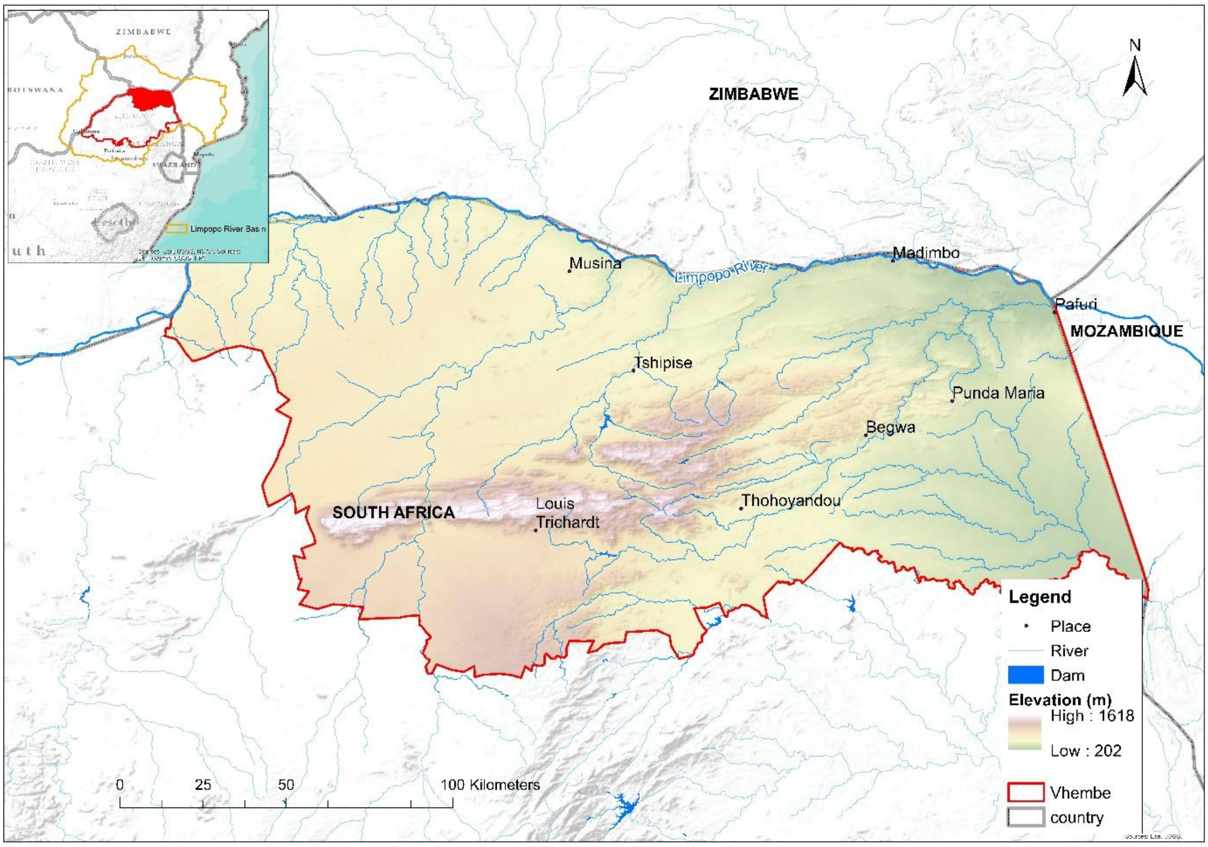

Figure 1. Vhembe District Municipality, South Africa.

The Climate Change and Vulnerability Assessment conducted in 2016 identified vulnerability indicators including elements of the WEF nexus that require immediate and effective interventions that would build the resilience of the socioecological system to climate change whilst also supporting socioeconomic development needs (Department of Environment, Forestry and Fisheries, 2020). Table 1 shows a summary of the key vulnerability indicators for the Vhembe district as well as the adaptive capacity of the municipality to respond. Most rural areas in the Vhembe District Municipality experience frequent shortages of reliable water resources, with the community relying on unclean open sources such as rivers and dams as well as groundwater resources. Additionally, water security in the district is threatened by the expansion of mining activities that use a large proportion of the water. Other water challenges in the district include poor water quality, drying up of groundwater, limited funding for new and maintenance of water infrastructure, theft and vandalism. About 66% of households have access to electricity while the rest rely on wood and other affordable energy sources. Most of the households involved in agriculture in the district depend on rain-fed agriculture for their livelihoods (Kom et al., 2020) whilst some small farming cooperatives depend on rivers in the Limpopo catchment for irrigation (See Figure 2).

Figure 2: Small farming enterprises in Vhembe that use irrigation to support their agricultural activities.

Table 1. Vhembe District Municipality key vulnerability indicators.

Theme	Indicator title	Exposure	Sensitivity	Adaptive capacity
Agriculture	*Change in crop production areas*	Yes	High	Low
	Increased exposure to pests and diseases	Yes	High	Low
Biodiversity and environment	*Loss of grasslands*	Yes	High	Low
Human health	*Increased water borne, and communicable diseases (typhoid fever, cholera and hepatitis)*	Yes	High	Low
	Increased occupational health problems	Yes	High	Low
Water	*Increased impacts of flooding from litter blocking sewer systems*	Yes	High	Low
	Less water available for agriculture and human consumption	Yes	High	Low

StatsSA (2016) indicated that the district has about 382 358 households and 51% are female-headed households. The key economic activities in Vhembe are mining, agriculture, and tourism (e.g. the Mapungubwe World Heritage Site, Vhembe Biosphere Reserve and Tshipise Forever Resort). Despite being a major source of income for the district through the production of vegetables, citrus, subtropical fruits, and nuts, agriculture has led to excessive usage of surface and groundwater for irrigation, as seen in the Sand Catchment, Nzhelele catchment, Mogalakwena River as well as the Albasini Dam (VDM, 2019). Water in the district is obtained from dams, rivers and boreholes but these are inadequate as some dams are over-allocated or have no allocation for domestic use (e.g. Nzhelele dam). Communities in Masisi have reported drying up of groundwater sources, pollution, theft and vandalism on borehole equipment (VDM, 2018).

The concerns for water security are compounded by the expansion of mining which also uses a large proportion of water in the municipality. Meanwhile, the municipality as a Water Services Authority and provider has noted challenges that make it difficult to effectively implement the water demand management strategy such as illegal water connections, delays in water meter installation, old infrastructure and water losses which are estimated at 20% of the total water produced within the schemes. The Vhembe District municipality Integrated Development Plan (IDP) reported that rural development in the district has been constrained by the land tenure system, limited access to business opportunities, high agricultural input costs, the lack of mechanized agriculture and disease outbreaks(VDM, 2022). Other issues identified are poor waste management, the prevalence of climatic disasters, non-compliance to environmental legislation (transport infrastructure, housing development and illegal sand mining) and uncoordinated planning and decision making, e.g. between traditional leaders and municipalities. Feasibility studies conducted in the district indicate that the municipality has the potential for alternative energy in form of biogas which can be used to meet the current energy needs of poor households. Vhembe has been collaborating with the Eskom, University of Venda, Gondal/CLGH to support the implementation of bioenergy and solar power as part of their green economy initiatives (VDM, 2019).

1.4.2. Narok County, Kenya

In Kenya, the selected study site is in Narok County in southwestern Kenya. The project specifically focused on some parts of the Mau Forest Catchment Basin (MFCB) which includes the Mau Water Tower also known as the Mau Forest or Mau Forest Complex. This is one of the five largest water towers in Kenya which support agriculture, tourism and hydro energy production (Odawa and Sewo, 2019). The MFCB encompasses three other counties which are Bomet, Kericho and Nakuru covering an area of about 273 300 hectares in the western parts of Narok County. Poverty is prevalent in the basin regardless of the abundant natural resources (Bomet 48.8%, Nakutu, 29,1% and Narok, 22.6%) (USAID, 2019). Figure 3 shows the extent of the study area which is part of the Mara river sub-basin in the west/southwest and the Ewaso Ng'iro South sub-basin in the north, central and east of the delineated study area.

The MFCB catchment provides several main rivers with water including the Mara River, Sondu Miriu, Southern Ewaso Nyiro, Nzoia, and Kerio, , all of which flow into Lake Victoria, and some into Lake Natron and Nakuru. The Sondu River is the site for the Sondu-Miriu hydro power plant and the catchment in general is estimated to have the capacity to produce 40% of Kenya's current generation capacity (UNEP, 2013). Studies have shown that water quality and quantity in the Mau Forest Water tower has declined due to rapid population growth in the area resulting in land use change and cover as well as loss of biodiversity. This is evidenced by a sharp increase in the area covered by grassland and a severe decline in forest cover which enhances the water towers' ability to replenish springs and rivers (KWTA, 2015). The population of Narok increased from 299, 319 in 1979 to 850 920 in 2009. Studies in the area also show that the catchment has been experiencing a decline in riparian vegetation, loss of soil and clearing of forests to expand human settlements as well as conversion to cropland (Matano et al., 2015; Odawa and Seo, 2019). Agriculture activities in the area include livestock rearing, maize and sorghum production, tea plantations and dairy farming. Forests have also been cleared for firewood as a primary source of fuel for cooking and logging. Efforts are being made by government agencies to support reforestation and delineate extremely critical water catchments and biodiversity hotspots for conservation (KWTA, 2015).

The site was selected as it provided opportunities to engage larger populations of both small-scale and large-scale farmers, stakeholders involved in energy generation and the county and sub-county government agencies (agriculture (crop and livestock), water, energy and environment/forestry) and other related stakeholders. The study area has one of the highest rainfall amounts in the country with mean annual rainfall averaging 750 mm and occurring during the November to December short rains season and the March to May long rains season. Nonetheless, some areas in the higher altitude areas and the western parts of the study area on the Mau forest Escarpment receive rainfall above 1000 mm per annum. However, rainfall in the area is characterised by inter-annual and decadal rainfall variability with frequent droughts every 5-7 years influenced by the El Nino Southern Oscillation. Similarly, temperature increases as altitude decreases with drier and warmer temperatures occurring in the northeast areas of the study area (USAID, 2019).

In Narok County, water quality and quantity have declined over the years. This has been attributed to among other things rapid population growth, pollution, changes in land use and land cover as well as loss of biodiversity as evidenced by a sharp increase in the area covered by grassland and severe decline in forest cover which enhances the water tower’s ability to replenish springs and rivers (KWTA, 2015; 2016). Like Vhembe, rain-fed agriculture dominates in Narok County with households growing crops such as maize, onions and legumes and commercial farmers growing similar crops as well as sunflower and cabbage among others (See Figure 4). Energy supply in Narok is mainly from hydro-power plants, e.g. the Sondu-Miriu hydro-power plant on the Sondu River however some households have no access to grid electricity and use charcoal, solar, kerosene and firewood. The use of charcoal and firewood has resulted in widespread deforestation in the country including in the Mau Forest. The county is also prone to climate change related hazards such as droughts and floods with impacts on various sectors including food, energy and water security.

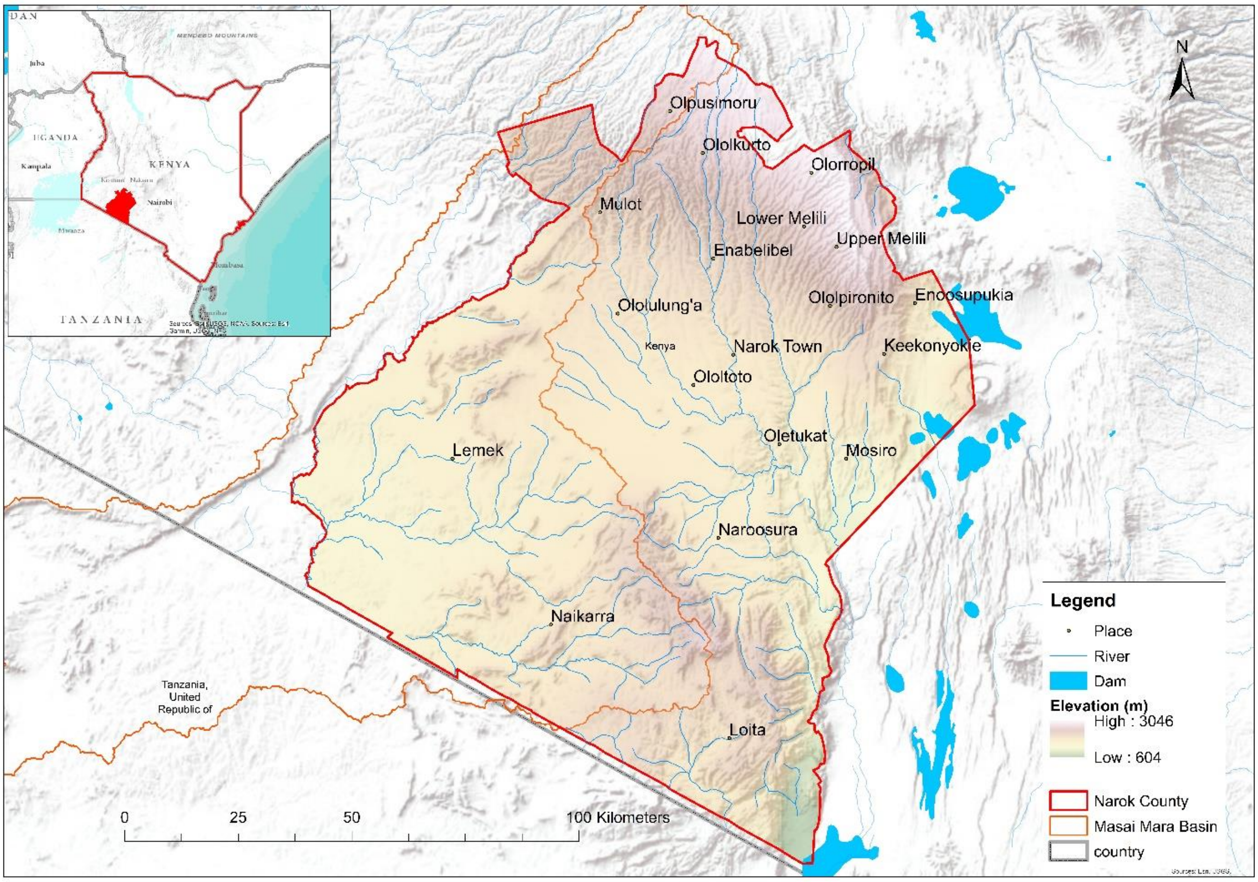

Figure 3. Narok County, Kenya.

Figure 4: Farming activities in Narok (commercial farming on the left and subsistence farming on the right).

2. LITERATURE REVIEW ON THE STATE-OF-THE-ART WEF NEXUS ASSESSMENT FOR SOUTHERN AND EASTERN AFRICA

2.1. Introduction

Sustainable resource management has become a major global challenge and concern over the last few decades. The increased demand for natural resources due to population and economic growth will exacerbate the challenge more and will have an impact on achieving the Sustainable Development Goals (SDGs) (SDGs, UN, 2015). Despite the adoption of initiatives such as the 2030 Agenda for Sustainable Development Goals (UN, 2015), many developing countries in Africa are still facing food, water and energy insecurities. Energy, water and food resource systems are intrinsically interconnected and are central to the global sustainability challenges (Nerini et al., 2017). For instance, energy is needed to produce food and to treat and distribute water. Water resources are required to cultivate food crops and to generate essentially any form of energy. Food, on the other hand, is needed to support the world's growing population that both generates and relies on energy and water services. Demand for water, food and energy is expected to rise by 30-50% in the next two decades, hence any strategy that focuses on one part of the water-food-energy nexus without considering its interconnections risks serious unintended consequences (World Economic Forum, 2011). Therefore, mitigating these challenges of access to clean water, energy and poverty in Africa requires an integrated approach and solutions to achieve SDGs and manage natural resources.

Recently, the water-energy-food (WEF) nexus has been under the spotlight as a means of better understanding the complex interactions among multiple resource systems. Although the linkages between the water, energy and food systems is not a new idea, the concept became prominent in 2011 when the Bonn conference on Water, Energy and Food Security and the World Economic Forum focused on the water-energy-food (WEF) nexus (Hoff, 2011). The WEF nexus is a systems-based approach that considers the interactions, synergies and trade-offs among water, energy and food. The WEF concept explicitly recognises water, energy, and food systems as both interconnected and interdependent (Bazilian et al., 2011). The WEF nexus is closely aligned with the SDGs, particularly SDGs 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy). The WEF nexus is one of the integrated new approaches and solutions to climate change, variability and adaptation, which is driven by energy use and land-use changes (Mpandeli et al., 2018, Bazilian et al., 2011; van Vuuren et al., 2012).

According to Keskinen et al. (2016), the WEF nexus can be viewed as, a) an analytical tool as it systematically uses quantitative and/or qualitative methods to understand interactions among water, energy, and food systems; b) a conceptual framework (a dominant view thus far) for it leverages an understanding of WEF linkages to promote coherence in policy-making and enhance sustainability; and c) a discourse, given that the concept can be used for problem framing and promoting cross-sectoral collaboration. Scholarly literature on the WEF nexus concept (Leck et al., 2015; Kulat et al., 2019), its interpretation (Endo, et al., 2017), novelty (e.g. Albrecht et al., 2018), analytical tools and methods (Endo et al., 2015; Albrecht et al., 2018; Wiegleb and Bruns, 2018), and criticism (Cairns and Krzywoszynska, 2016; Simpson and Jewitt, 2019) have rapidly expanded illustrating the inherent potential of the nexus approach to contribute to the achievement of the SDGs.

The analysis of issues related to water, energy, food and the ecosystem through a nexus approach, has attracted the interest of scientists, policymakers and the private sector. To date, the number of studies on the WEF nexus is increasing rapidly focusing mostly on the improvement of the nexus approach concept, methodology, and nexus challenges (Endo et al., 2017). Many of these nexus studies have considered water as the central element mainly because the WEF nexus concept was originally developed within the water sector from water research projects (Aboelnga et al., 2018a, 2018b). For example, in South Africa, the Water Research Commission (WRC) has been championing the WEF nexus approach since its prominence in 2011. Globally, there are three studies (Newell et al., 2019; Chen et al., 2019; Opejin et al., 2020) conducted on bibliometric analysis of the WEF nexus and linkages between the WEF systems, to advance and refine the WEF nexus literature. These studies have shown that the WEF nexus research has expanded well globally, however, there is a limited number of WEF nexus studies reported for the continent of Africa. This research project focuses on the WEF nexus assessment for southern and eastern Africa by identifying the status, and review of existing WEF policies and strategies. The purpose of this study is, therefore, to conduct a bibliometric analysis of the WEF nexus literature globally and in Africa mainly focusing on eastern and southern Africa. The objectives of this study are to assess publication trends and geographic focus of research, identify research themes and questions, assess the integrated nature of the WEF research, and understand the challenges developments and the ways forward.

2.2. Data and Methods

The data analysed in this bibliometric review study were generated from a combination of diverse search topics within the WEF nexus subject matter. These search topics covered areas around policy and decision-making, governance and trade-offs, interdisciplinary analysis and transdisciplinary approaches, WEF climate and security nexus, and general case studies conducted on the WEF nexus. The search for documents was done using the Web of Science (WoS) and Scopus core collection databases. The first search covered the global scale, with no restrictions set for the period of review study, with the understanding that the WEF nexus is a newly developing field of research. The second search was restricted to WEF nexus research in Africa, again with an open-ended search period. An example of a WEF nexus search topic was set as follows, in both WoS and Scopus: “water-energy-food nexus governance” OR “water-energy-food nexus policy” OR “water-energy-food nexus decision making” AND “Africa”. The global search resulted in 1678 and 1881 retrieved documents from WoS and Scopus, respectively. In Africa, 130 and 107 documents were retrieved from the WoS and Scopus, respectively. The final documents considered for the review study after data pre-processing were 778 and 45 for global and continental scales, respectively. The data included a wide range of document types, e.g. articles, reviews, conference papers, and chapter books, among others. The data were analysed using bibliometric software, whereby different subfields were identified and analysed. These subgroups included citations analysis, keywords co-occurrence analysis, collaboration analysis and thematic analysis. The VOSviewer was used to visualize the subgroups' output and generate network maps. The workflow used to conduct science mapping in this review study, based on bibliometric analysis methods, is summarized in Figure 5. For more details on the bibliometric methods, the reader is referred to Zupic and Cater (2015), Aria and Cuccurullo (2017), and references therein.

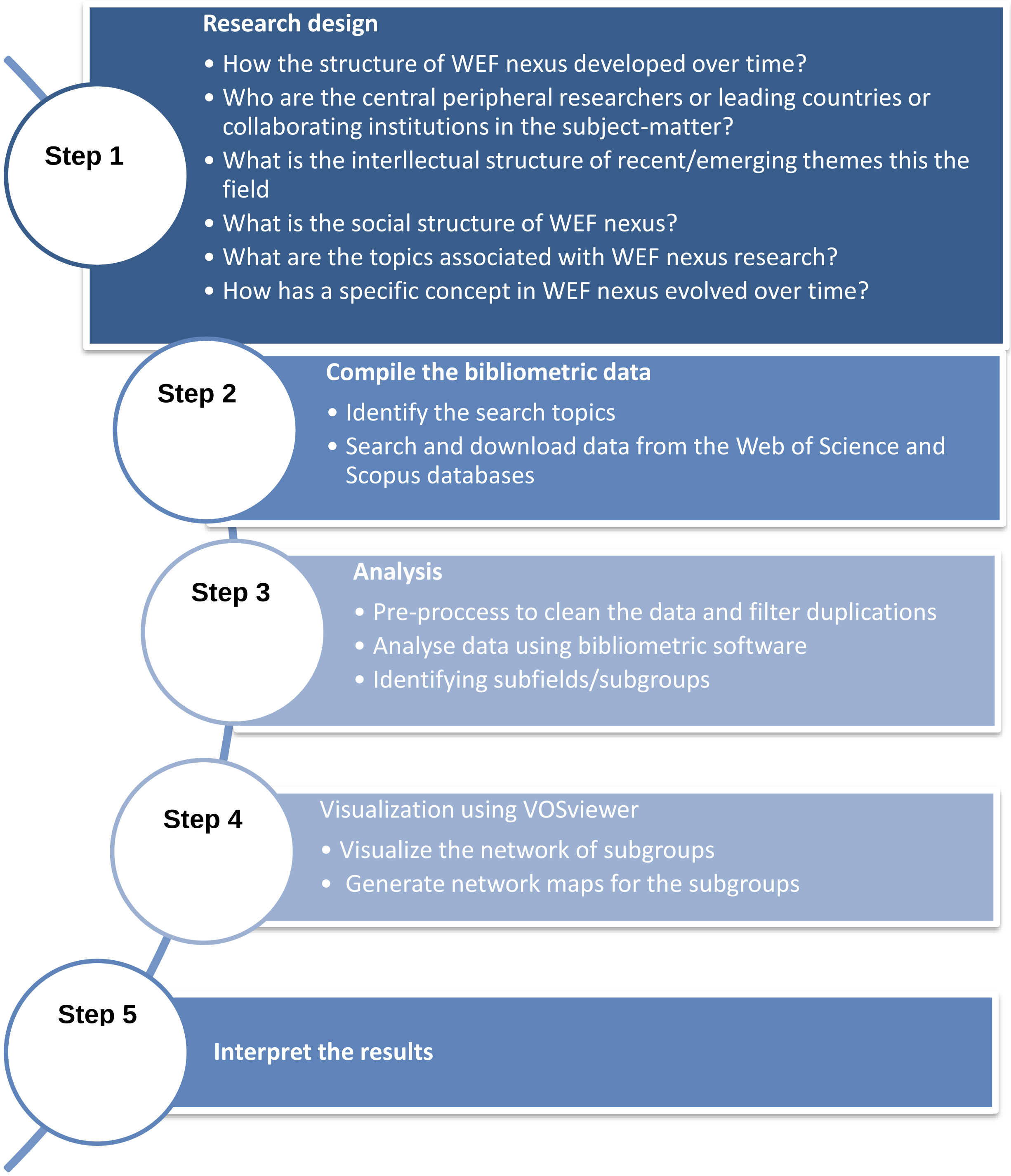

Figure 5. Schematic flow of the method of analysis, adopted from Zupic and Cater (2015).

2.3. Results

2.3.1. Annual Scientific Publications Growth

Figure 6 depicts the annual distribution of research articles published on the WEF nexus, globally from 2012 to 2020. The number of scientific publications relating to research on the WEF nexus from a global perspective remained limited between 2012 and 2014. An increase in the number of scientific publications began to noticeably emerge in 2015, with a steady continuous increase observed from 2016. The year 2019 was the most productive in terms of annual scientific publications, reaching the top-notch number of 213 published articles. Based on the results, scholars in the last four years, have shown increasing interest in WEF nexus research in support of integrated solutions for sustainability Overall, the annual scientific publications, recorded globally, from 2012 to 2020 showed a significant increase, with the annual percentage growth rate of approximately 81%.

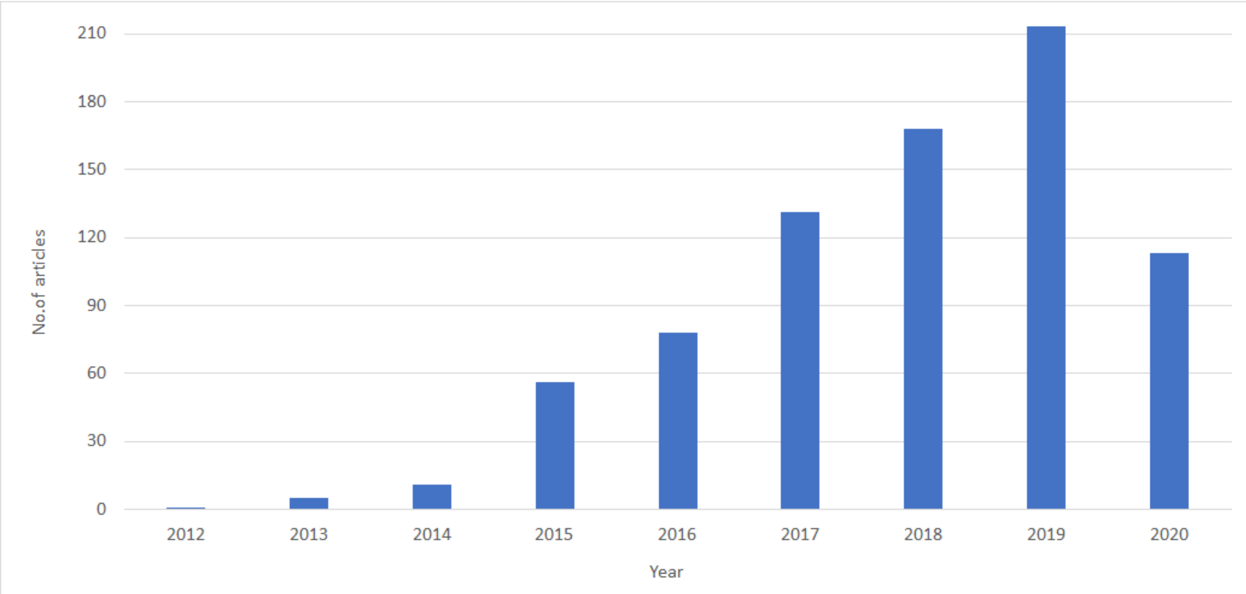

Figure 6. Annual scientific publications of WEF nexus based on a global perspective.

The annual distribution of scientific papers associated with the WEF nexus published in Africa from 2013 to 2020 is illustrated in Figure 7. Generally, continental research studies appear very limited, as compared to global studies. Few research articles on the WEF nexus were released between 2013 and 2016, with exceptions to 2014. A slight increase in annual scientific publications is observed between 2017 and 2018, with the highest peak reached in 2018.

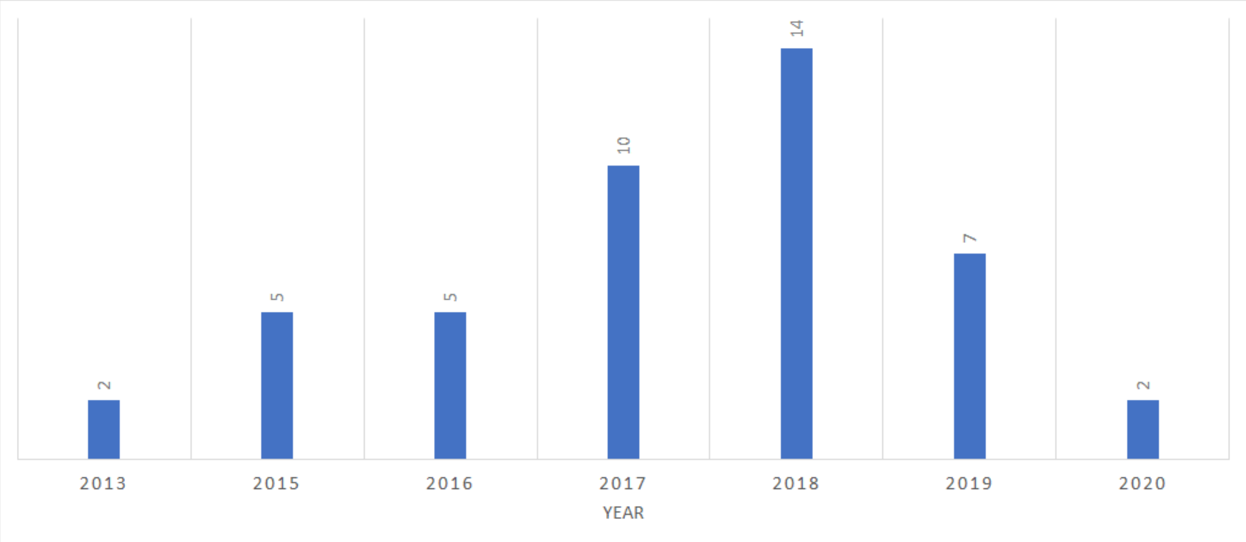

Figure 7. Annual scientific publications of WEF nexus in Africa.

2.3.2. Most Productive Countries in Scientific Publications of WEF Nexus Research

The scientific contribution of 15 top countries globally on the WEF nexus subject matter is shown in Figure 8, with more details given in Table 2. As can be seen in Figure 8, the United States of America (USA) has published more articles (82) over the considered review period, with 71 published under Single Country Publications (SCP), and 11 through Multiple Country Publications, (see details in Table 2, which include the number of citations per article). Germany rates second, with 36 SCP, followed by the UK and China with 33 and 31 published articles, respectively. In Africa, South Africa (SA) has published more articles (9), followed by Egypt with 5 scientific articles. A large percentage of the published articles in SA was published through an SCP as opposed to MCP. In terms of citation output, the USA received the highest citation records of 883, followed by the UK with 749. Interestingly, Japan, ranking 7th in the list, received the highest citation output of 22%, approximately 10% higher than other leading countries.

The ten topmost productive countries in Africa are depicted in Figure 9. This analysis was solely based on the affiliation of the first author in the articles. Generally, all countries are dominated by articles written by domestic authors, represented as SCP in the figure. South Africa and the UK have the highest publications, most of which were a result of SCP. Australia and Italy rank third, followed by the remaining six listed countries whose articles resulted from an SCP. Articles written in Belgium featured authors from different countries showing considerable interest in international collaboration.

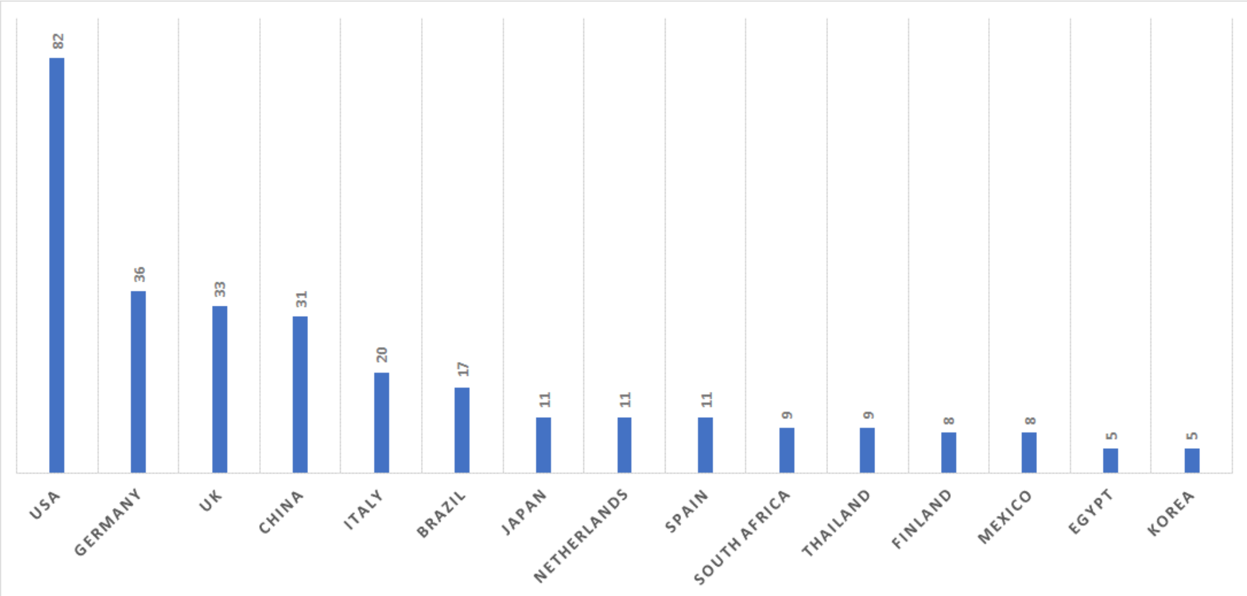

Figure 8. Top 15 countries in scientific publications of WEF nexus research globally.

Table 2. Most productive countries in scientific publications of WEF nexus research globally based on the affiliation of the corresponding author's countries. SCP: Single Country Publications; MCP: Multiple Country Publications.

Country	Articles	SCP	MCP	Total citations
USA	82	71	11	883
Germany	36	36	0	327
United Kingdom	33	30	3	749
China	31	27	4	203
Italy	20	18	2	163
Brazil	17	15	2	44
Japan	11	10	1	249
Netherlands	11	11	0	45
Spain	11	10	1	71
South Africa	9	7	2	63
Thailand	9	7	2	
Finland	8	8	0	120
Mexico	8	8	0	
Egypt	5	5	0	
Korea	5	4	1	

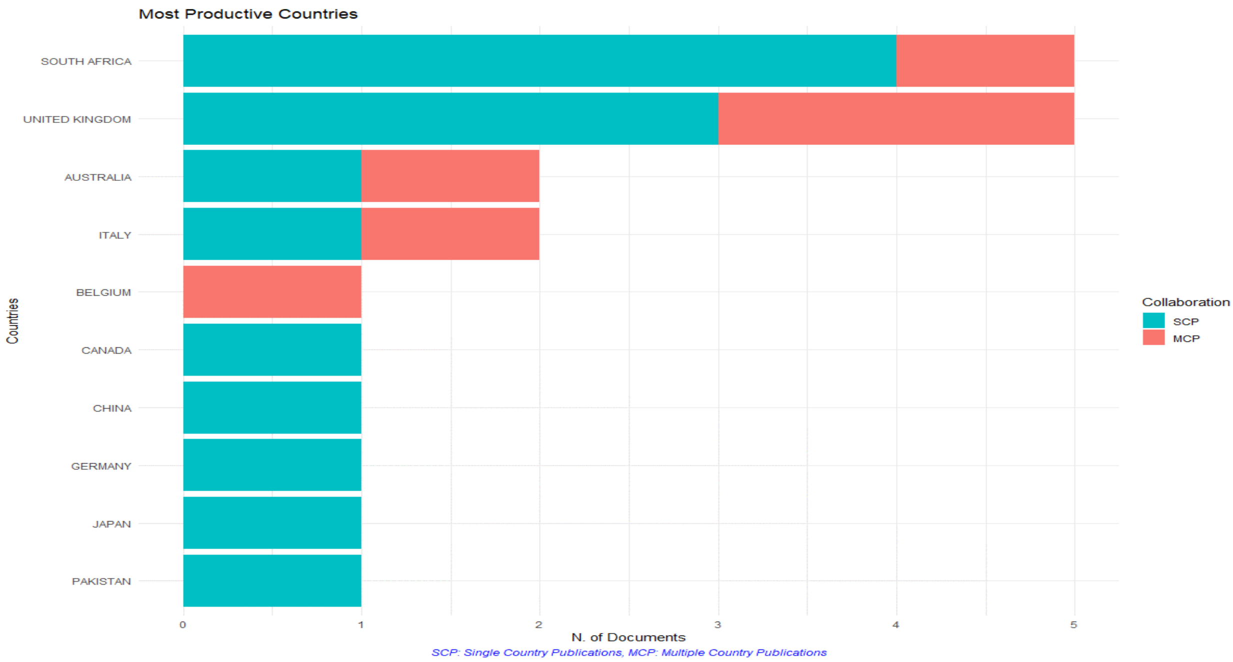

Figure 9. Top 10 countries with scientific publications of WEF nexus research in Africa.

2.3.3. Collaboration Network

2.3.3.1. Country Collaboration Network

Figure 10 depicts a collaboration network between countries based on a global perspective. The countries were assigned into four (4) respective clusters, each country assigned only once. In each cluster, the size of the cluster ranks the collaboration of the country. For instance, countries in bigger clusters show strong collaboration patterns while those in smaller size clusters have limited collaborations with other countries. Based on this interpretation, we note that the USA in the teal cluster, is at the centre of the global collaboration network, cutting across continents with 24 links. Italy, the UK and Spain dominate in the red cluster, with 11, 7 and 6 links respectively. Sri Lanka in the blue cluster leads with 11 links; the Netherlands, Norway, Germany and Austria in the green cluster dominate with 8 links each; whereas China is the leading collaborative country in the purple cluster. For the southern hemisphere countries, Australia and SA in the yellow cluster were leading in collaborations. Overall, collaboration among countries in WEF nexus research, particularly for Africa is inadequate. Collaborations among countries promote the level and quality of scientific research, gather innovative ideas and cultivate new and comprehensive scientists. Through greater collaboration on both the regional and international platforms, knowledge in the management and allocation of water, energy and food resources will be enhanced in support of sustainable development.

Figure 11 shows the distribution of countries that collaborated on WEF nexus research focusing in Africa. As depicted in Figure 7, countries leading in WEF nexus research in Africa are SA, Kenya, Morocco and Niger. For all four countries, collaboration with international countries is limited to the USA and several countries in

Europe, including the UK, Spain and Turkey. The southern hemisphere collaboration is noted yet again for SA and Australia, with Kenya emerging as a growing collaborator. Niger, a country located in West Africa, has strong collaboration links with New Zealand, Italy and Spain.

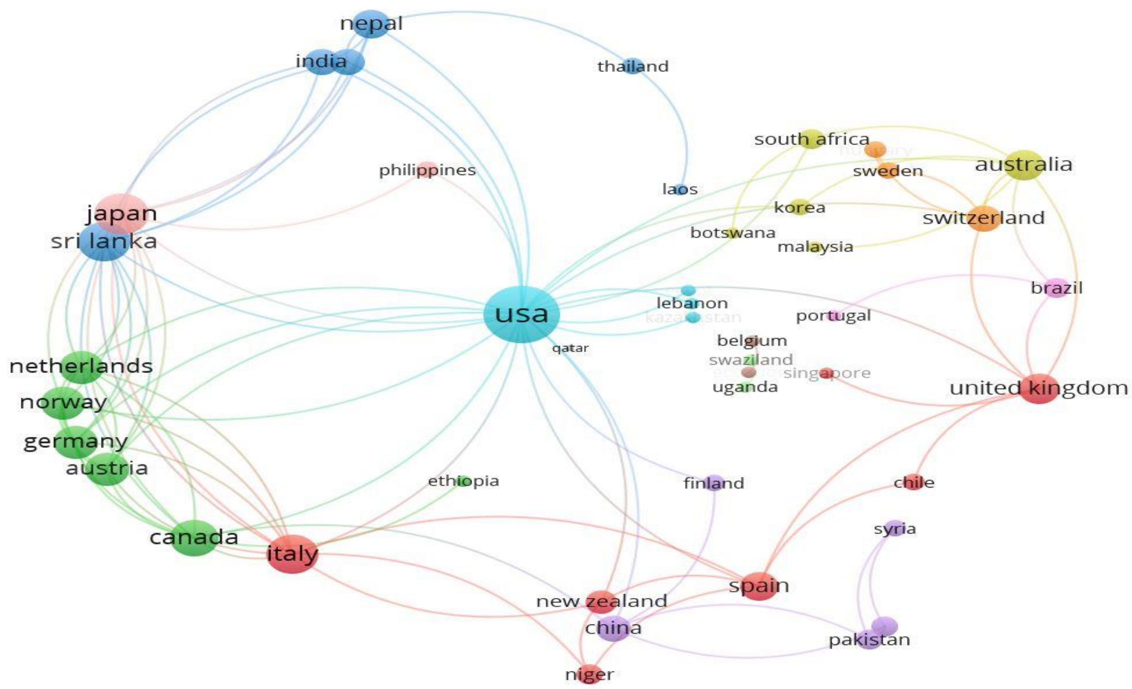

Figure 10. Countries' collaboration network, at a global scale

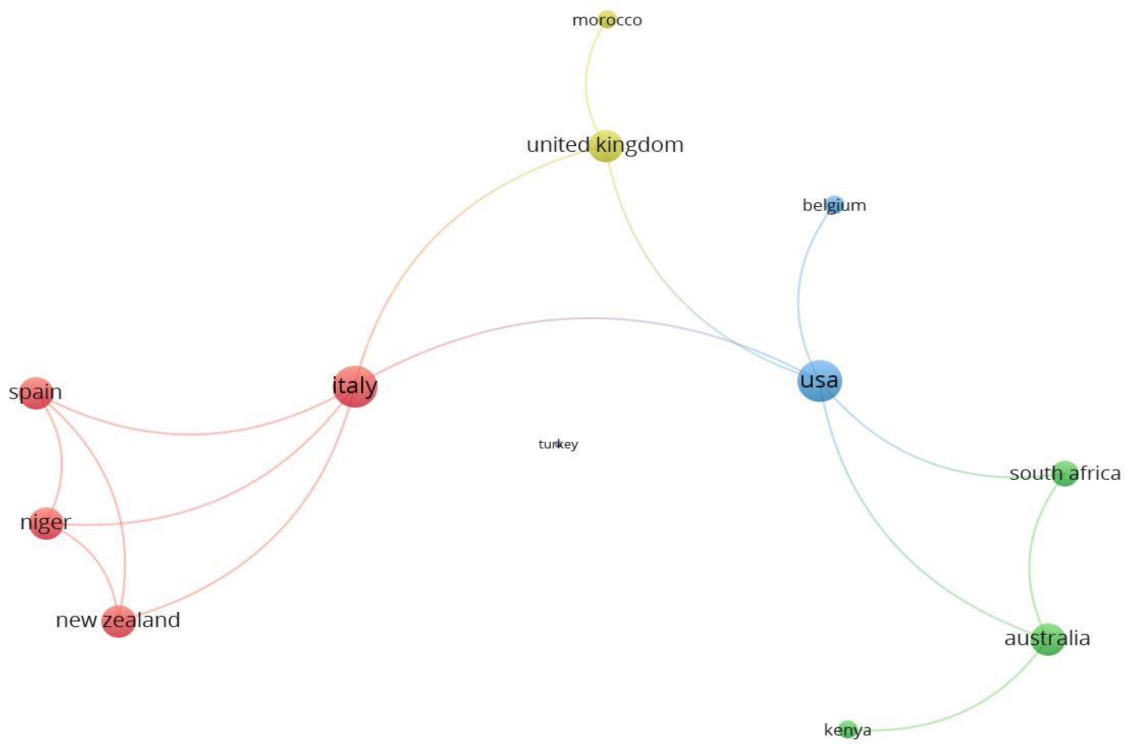

Figure 11. Countries' collaboration network on WEF nexus research in Africa.

2.3.3.2. Institutions Collaboration Network

As depicted in Figure 12, the collaboration among universities and institutions on a global scale is quite dense. Leading universities per cluster: pink cluster – University of York (70 association links) and the University of Cambridge (38 association links); orange cluster – Baylor University with 50 links, purple cluster – University College London with 25 links, teal cluster – the National University of Singapore with 47 links followed by the University of Hong Kong with 37 links, blue cluster – the University of Exeter with 50 links and red cluster – International Food Policy Research Institute and the University of Geneva with 29 and 25 association links, respectively.

Six major clusters which suggest strong collaboration among African institutions are shown in Figure 13. In the red cluster the University of Kwa-Zulu Natal, in SA, is seen to be dominating, showing strong links with the University of Venda and the Water Research Commission. Research within this cluster is tight to three international institutions, including the International Water Management Institute (IWMI), International Rice Research Institute (IRRI) and the Delft Institute for Water Education (IHE-Delft), based in Delft, the Netherlands. The International Food Policy Research Institute (IFPRI), an international agricultural research centre in the orange cluster is the central link between the teal, blue and green clusters. Lead institutions in the latter cluster are mostly in SA. These include the Council for Scientific and Industrial Research (CSIR), the University of Pretoria and the University of the Witwatersrand. The international collaboration in this cluster is given by the Humboldt University of Berlin and the London School of Economics. Institutions in the blue cluster have no direct links to institutions in Africa except through IFPRI. This cluster consists of two institutions in the USA, and one in China, Japan and Canada, respectively. Three international institutions in the teal cluster have collaboration with the Kwame Nkrumah University of Science and Technology, in Ghana.

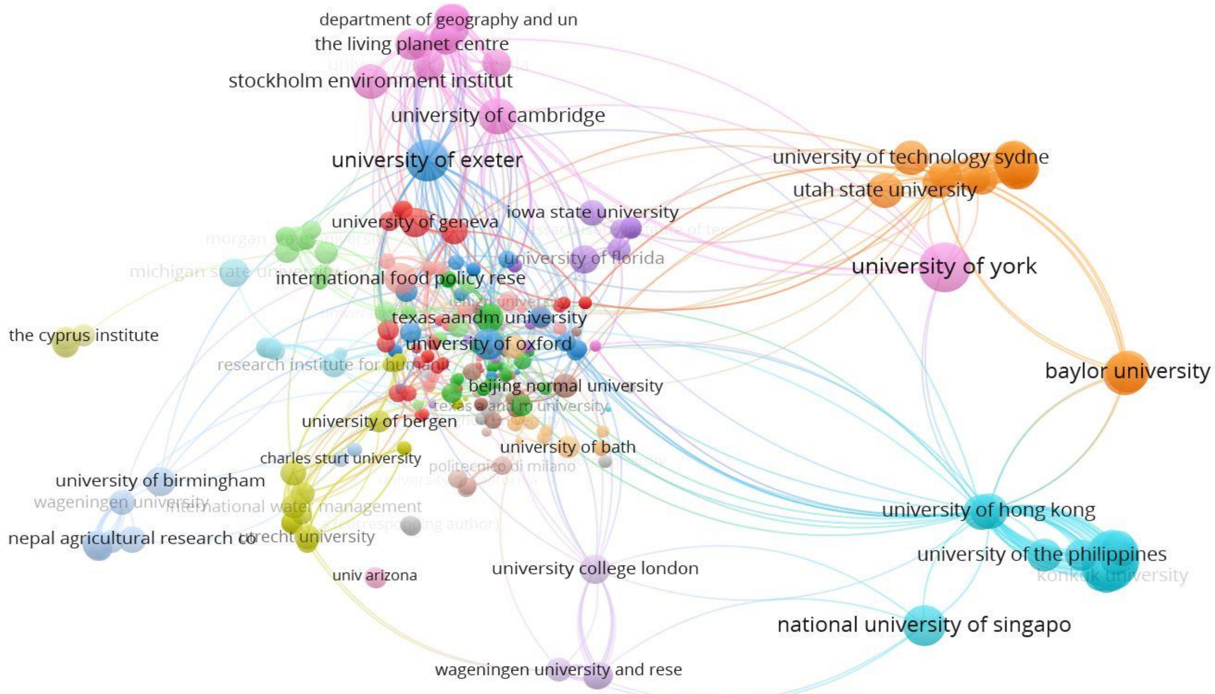

Figure 12. Institutions collaboration network based on global scientific publications

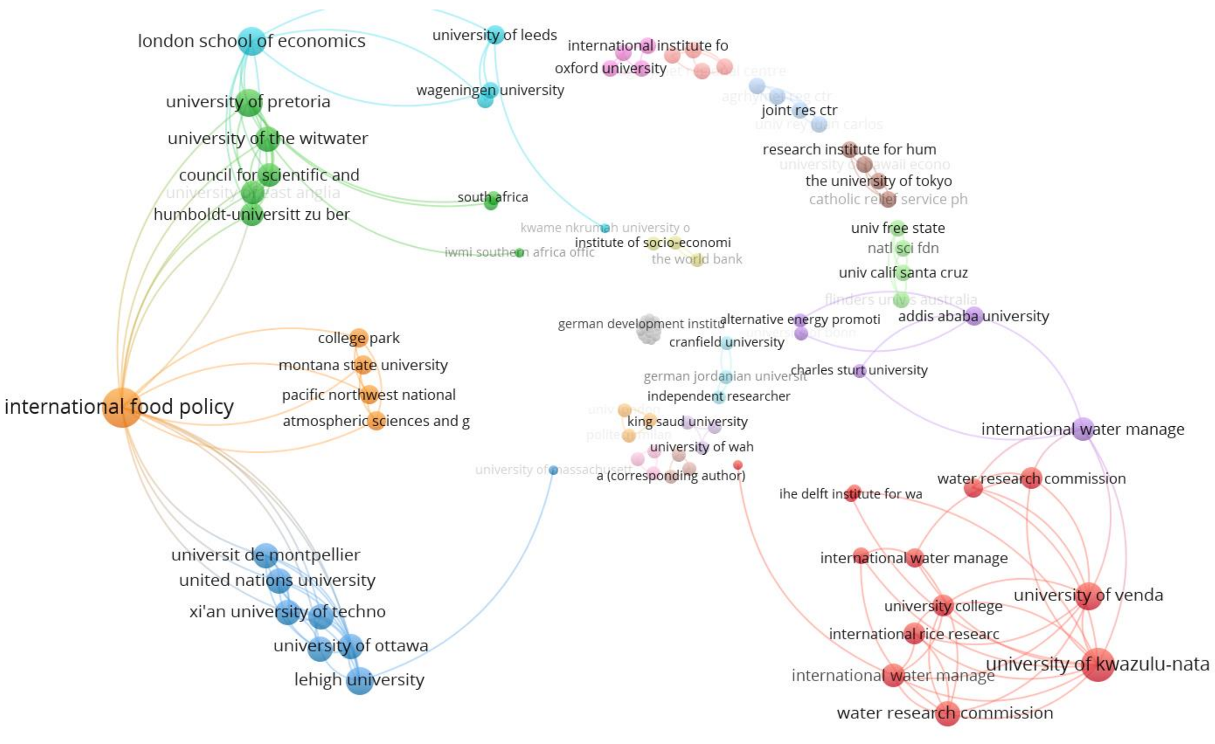

Figure 13. Institutions collaboration network based on African scientific publications.

2.3.4. Co-Words Analysis

2.3.4.1. Keywords Co-occurrence Analysis

Figure 14 depicts the keywords co-occurrence network from the global scientific publications on WEF nexus research, visualized from VOSviewer. The keywords were grouped into three main clusters. The dominant keywords appearing in the red cluster include water resources, water management, water supply, and water use. Included also in this cluster are keywords related to agricultural research, such as land use, crops, food security, and resource management. The main keywords in the green cluster, are sustainable development, food security, water conservation, hydroelectric power, environmental protection, environmental policy, energy and water supply. The blue cluster has the following dominant keywords: wastewater treatment, water treatment, gas emissions, and greenhouse gases among others.

Figure 15 depicts the most dominant keywords co-occurrence network extracted from 45 scientific articles published in Africa between 2013 and 2020. In the visualization presented in the figure, the keywords can be classified into four main clusters. In the green cluster, there are five leading keywords including food supply, food security, agriculture and water resource. Sustainable development, climate change, water supply and sustainability are the main keywords appearing in the blue cluster. At the same time, sustainability appears to dominate in the yellow cluster. The red cluster is dominated by keywords such as biodiversity, governance, resource management, environmental management and river basin, among others.

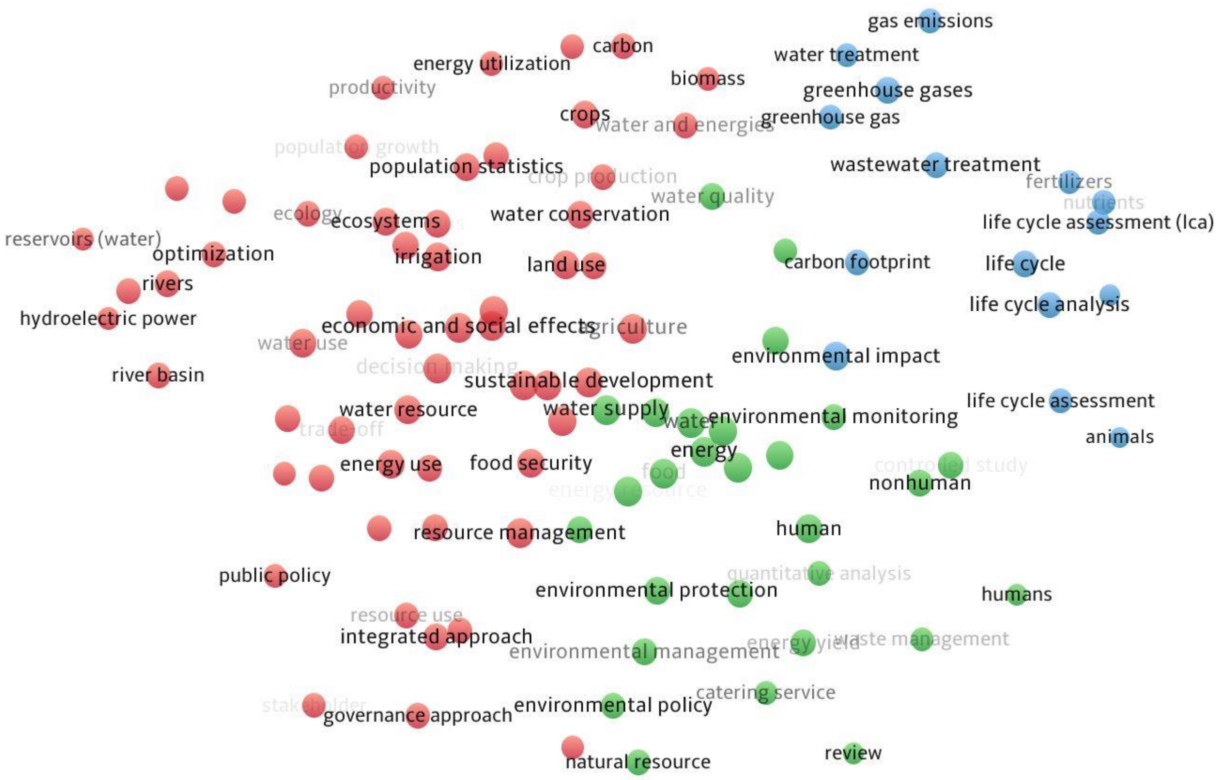

Figure 14. Keywords co-occurrence in globally published articles on WEF nexus.

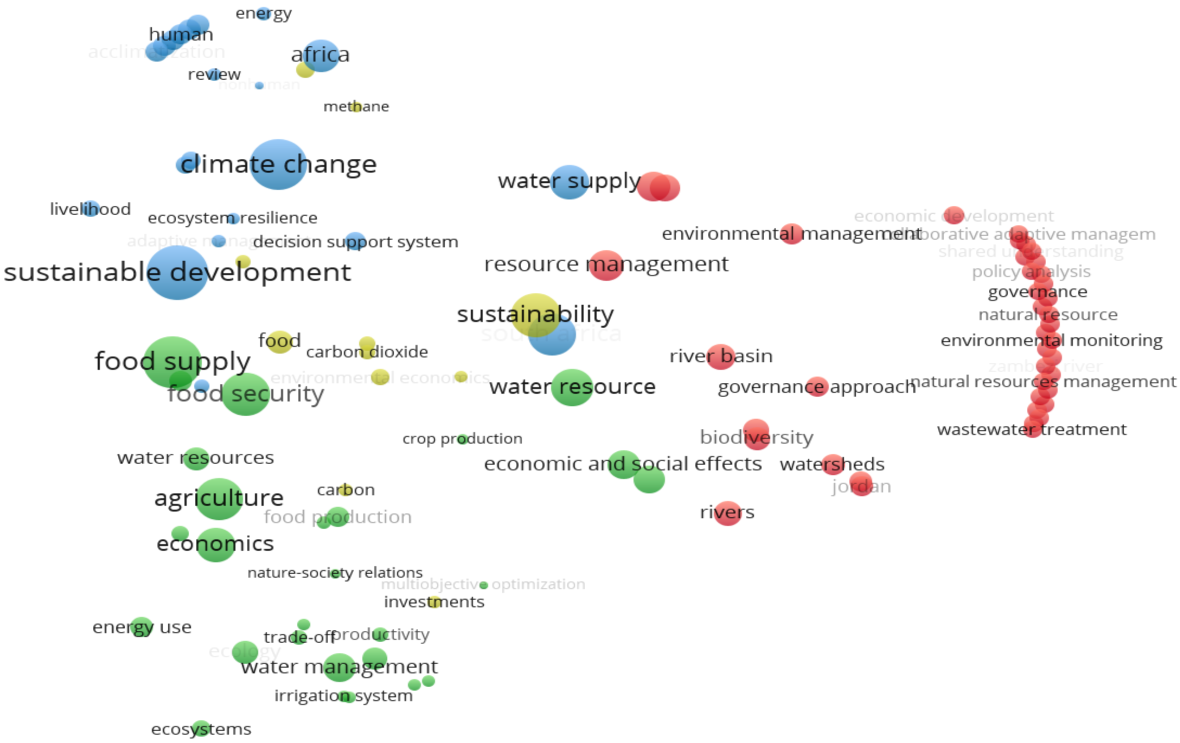

Figure 15. Keywords co-occurrence in published WEF nexus articles in Africa.

2.3.4.2. Multiple Correspondence Analysis

The co-word analysis was carried out using Multiple Correspondence Analysis (MCA), an approach used to examine the relationship between keywords, i.e. to identify clusters of articles that articulated common concepts (Clausen, 1998). The results of this analysis are shown in Figure 16. As shown in the figure, the keywords are clustered into four groups (clusters. Words like watersheds, rivers or river basins and hydroelectric power are grouped in the purple cluster. These keywords share a common concept relating to surface water. The blue cluster contains keywords such as crop production, food industry, irrigation agriculture and environmental management, sustainability and impact. Most of the keywords in the blue cluster share a common concept that relates to agriculture and the environment. The widest red cluster illustrates a wide range of emerging research themes, with keywords that have concepts of policy and decision-making, water resource management and planning, risk assessment, energy, and greenhouse gas emissions. Based on the combination of keywords appearing in the red cluster, the clustered document cannot be used to build an effective structural concept. In this case, the red cluster only represents the centre of the WEF nexus research, rather than a common concept of a research theme.

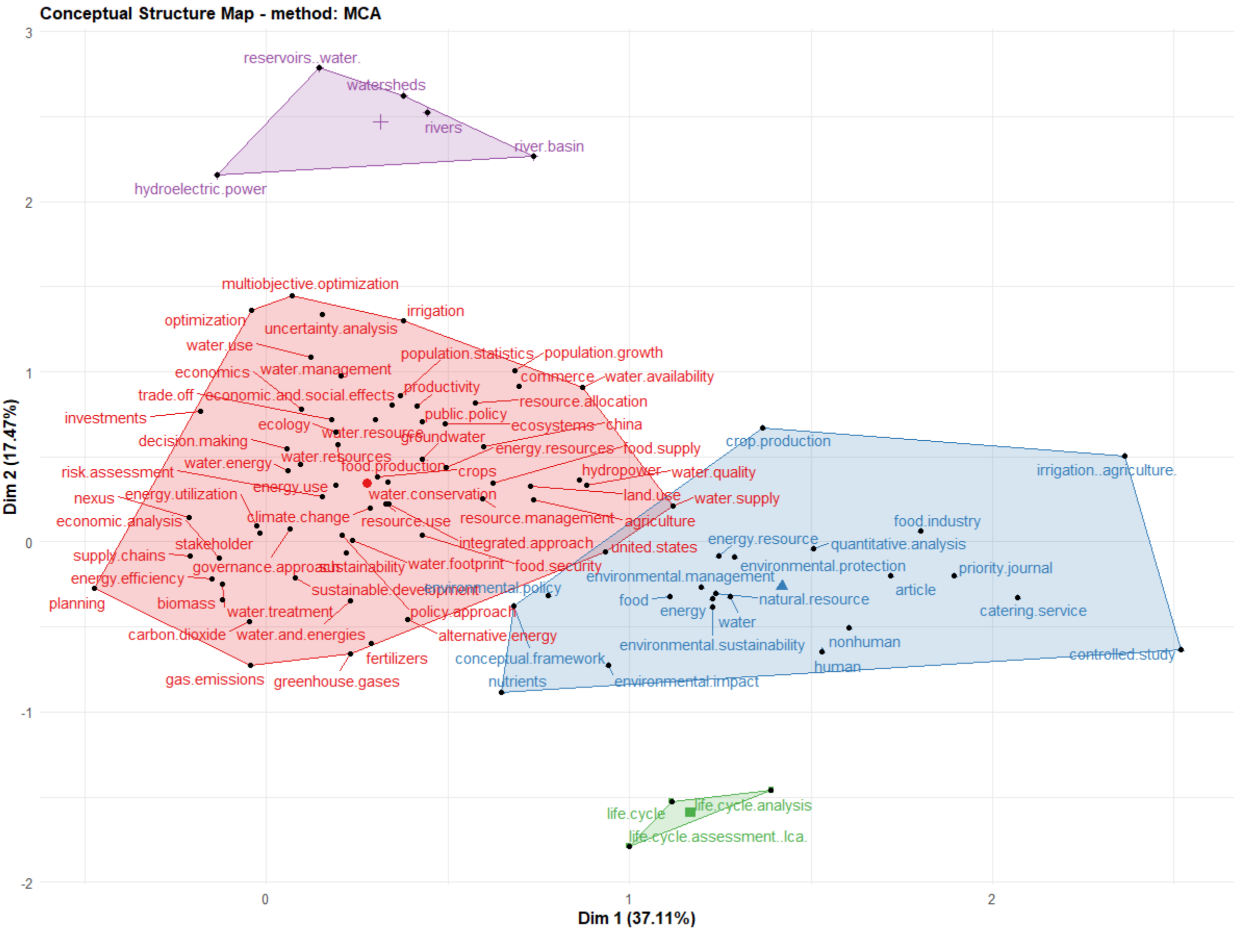

Figure 16. Conceptual structure map based on multiple correspondence analysis.

2.3.5. Thematic Analysis

Figure 17 and Figure 18 depict thematic maps for the global and continental WEF nexus research studies, respectively. In both figures, themes appearing in the upper-right corner of the quadrant are referred to as motor themes, and they represent strong centrality and high density (Lulewicz-Sas, 2017). In each figure, themes appearing in the upper-right quadrant (e.g. environmental impacts, life cycle assessment, and water supply as well as water resources, management and supply, climate change and decision-making (in Figure 18) are considered as well developed and important for the structuring of WEF research. For the region (in Figure 18), there is strong centrality and high density, indicating that researchers are paying close attention to the topic. Exploring these topics is important to enhance knowledge in the field, which will sequentially inform policy and support implementation within WEF nexus sectors. Themes appearing in the upper-left quadrant (e.g. environmental sustainability, ecosystems and biomass for global WEF nexus research) are well established but only internal, hence such themes are marginally important in the WEF nexus field of research. Themes in the lower-left of the quadrant, for instance, African context, e.g. environmental policy, hydropower, ecosystems and energy use are considered as weakly developed, have low density, low centrality and are either emerging or disappearing. Themes like sustainability development, agriculture, food production and water management, appearing in the lower-right quadrant of Figure 18 are essential for the WEF nexus research but are still in the developing stage.

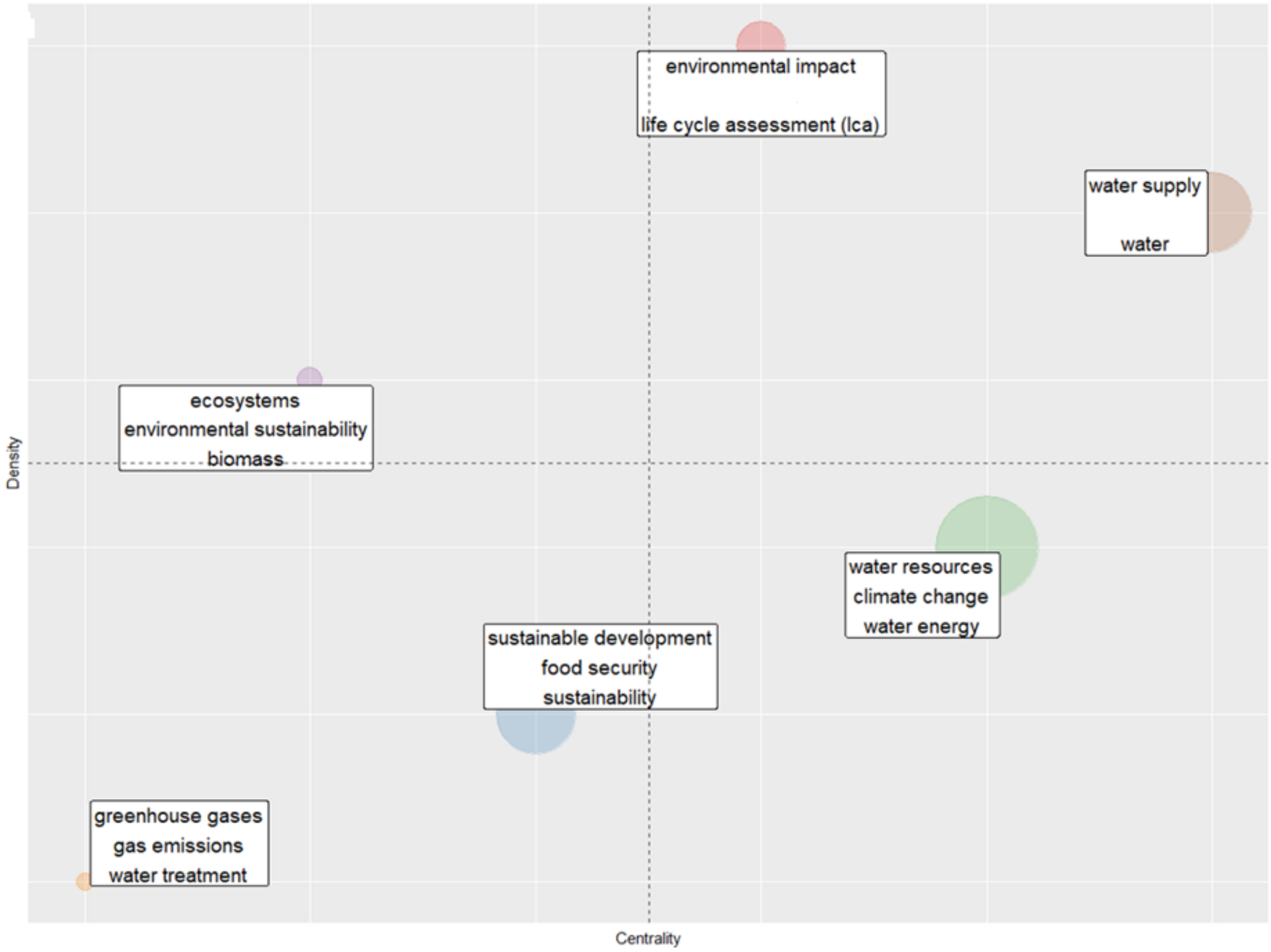

Figure 17. Thematic map computed from global WEF nexus research scientific publications.

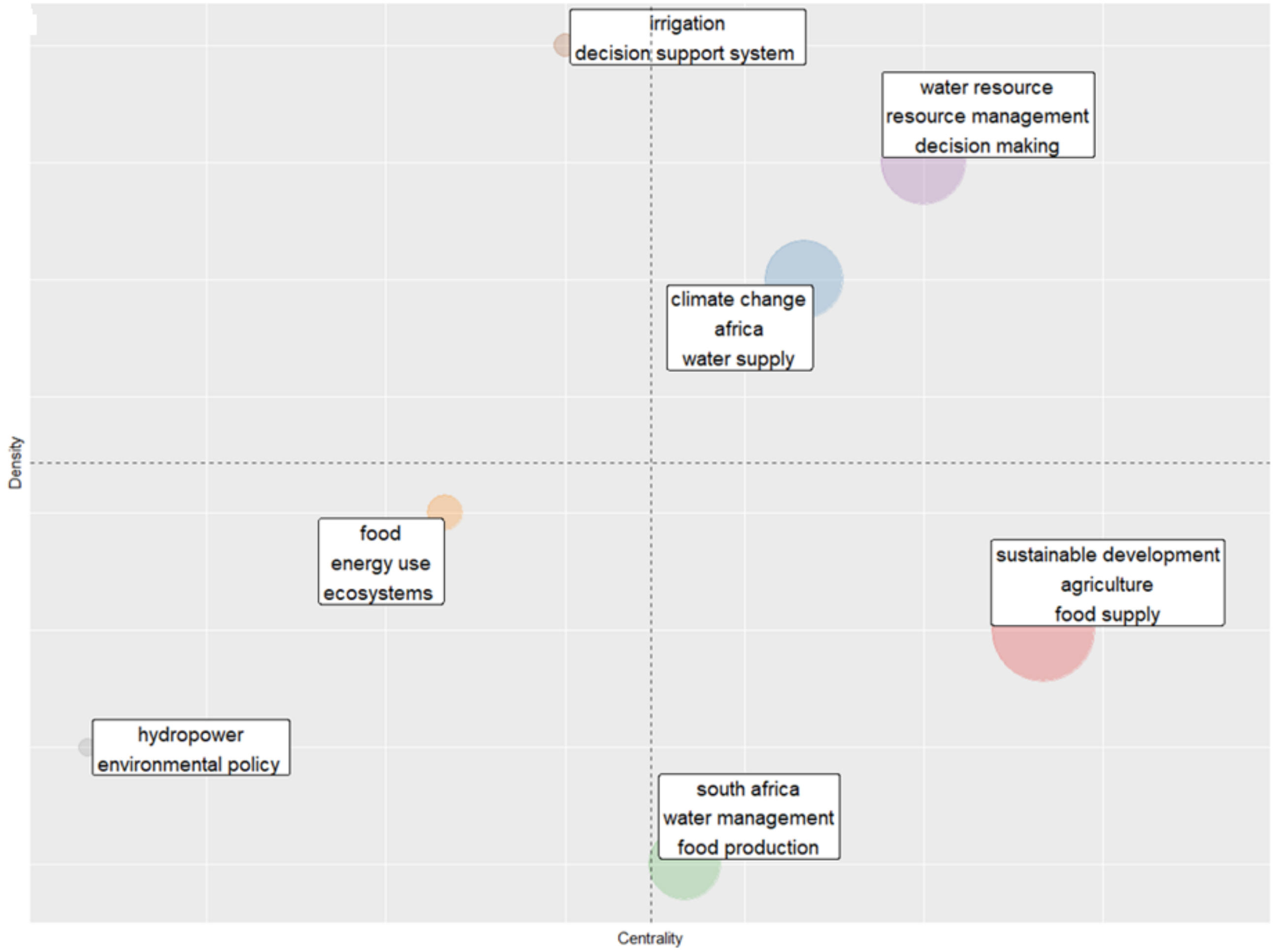

Figure 18. Thematic map computed from scientific articles published in Africa.

2.3.6. Direct Citation Network

The intellectual structure of global WEF Nexus research is developed by a historical direct citation network that deploys a chronological citation network (Figure 19). According to Borgman and Furner (2002), a historical direct citation network represents a chronological map of the most relevant citations resulting from a bibliographic collection, in this case globally from 2012-2020. The interesting aspect of this visualization is not the name of the authors as such but rather the topics, methodology, findings and knowledge generated or proposed for the WEF Nexus. Consequently, the studies are reviewed to detect the connectivity in terms of methodological approach, and findings including identifying research gaps and research recommendations. A summary of the WEF Nexus studies is given in Appendix 1.1.

As depicted in Figure 19, two clusters can be identified; the red and blue clusters indicate an assemblage of articles having a direct citation. The earliest cluster is the red cluster, which started with the study by Kirsop-Taylor et al. (2012) who investigated the conceptualization of WEF nexus as a tool to frame and understand the social-ecological complexities facing Natural Resource Management (NRM) agencies using organisational cultural narratives. The results suggested that the narratives of Communication, Collaboration, Trust and Empowerment (CCTE) might be utilised to mobilise the cultural changes needed to meet complex configurations of social-ecological expectations for a tool such as the WEF nexus within challenging political and economic contexts. This research was later cited in five research studies (e.g. Leck et al., 2015; Cairns et al., 2016; Zhang et al., 2018, Pueppke et al., 2018; Rey-Mahia et al., 2019). Studies by Leck et al. (2015) reviewed the premise of initiatives framed around the “nexus” and examined the challenge of achieving the type of disciplinary boundary crossing promoted by the nexus agenda.

According to the findings, the nexus has encountered significant barriers to progress, including challenges to cross-disciplinary collaboration, complexity, political economy (often perceived to be under-represented in nexus research) and incompatibility of current institutional structures. It was concluded that greater recognition of interdependencies across state and non-state actors, more sophisticated modelling systems to assess and quantify WEF nexus linkages and the sheer scale of WEF resource use globally, could create sufficient momentum to overcome historical barriers and establish nexus approaches as part of a wider repertoire of responses to global environmental change. On the other hand, studies by Cairns et al. (2016) examined how nexus terminology is emerging and being mobilised by different stakeholders in natural resource debates in the UK context, suggesting the importance of critique to the development of nexus research. Zhang et al. (2018) developed an integrated model analysis framework and tool called WEFO which provides a multi-period socioeconomic model for predicting how to satisfy WEF demands based on model inputs representing production costs, socioeconomic demands, and environmental controls. The model parameters were analysed using global sensitivity analysis and their effects on total system cost were quantified. According to the authors, the developed model can be used to support decision-makers and stakeholders in making cost-effective decisions for optimal WEF management. Pueppke et al. (2018) proposed the use of the interrelationships between WEF and the vulnerability of these components to climate change for the ecological management of river catchment. For effective use of the concept, the authors proposed the participation of interdisciplinary teams of researchers with both tacit and specialized knowledge. On the other hand, Rey-Mahia et al. (2019) investigated the concept of WEF nexus for the ecological sustainability of ground source heat pumps. The authors recommended the use of the WEF nexus concept, suggesting that it has the potential to provide for adequate climate and socio-ecological change adaptation measures.

In summary, the first citations dealt with the topic of reviewing the WEF nexus and its usefulness for ecological sustainability to establish a holistic view and understanding of the concepts of the WEF nexus. Studies by Leck et al. (2015), generated several direct citations (Jalilov et al., 2016; Perrone et al., 2016; Biba, 2016). These studies expounded on the concept of Leck et al. (2015) to examine trade-offs between allocating water for food and water for energy and the influence of climate variability and change. The studies advocated for a strong inclusion of political and community buy-in for successful WEF nexus implementation. The secondary citations included the studies by El-gafy et al. (2017), Wallington et al. (2017), Gondhalekar et al. (2017), Wichelns et al. (2017) and Belmonte et al. (2017). These studies investigated the concepts of the WEF nexus and its implementation. The studies revealed that the implementation of the WEF nexus can improve food security and sustainability.

The studies further indicated the need to balance WEF nexus implementation with policy. Other studies (e.g. Bellezoni et al., 2018; Kibler et al., 2018, Saladini et al., 2018; Pasqual et al., 2018; Burnett et al., 2018; Terrapon et al., 2018; Stein et al., 2018; Hussien et al., 2018; and Venghaus et al., 2018) examined the concept of economic-ecologic interactions. These studies expounded on previous research to establish the response or consequences of choice trade-offs among WEF nexus implementation. The concepts were further amplified in WEF nexus research for 2019 as demonstrated in the works of Gurusamy et al. (2019), Grigg (2019), Ju et al. (2019), Mansoor et al. (2019), Jin et al. (2019), Nassani et al. (2019); Hersh et al. (2019); Sani et al. (2019), Lahmouri et al. (2019) and Fernandes Torres et al. (2019). These studies emphasized the need for an integrated methodological approach to the WEF nexus. The 2020 research (Anser et al., 2020; Putra et al., 2020; Villamor et al., 2020; Gedefaw et al., 2020; Daher et al., 2020) investigated the role of land-use change and its causal effect on climate change in the actual implementation of WEF nexus. Many of these studies were carried out in the US. The studies were geared towards food and energy sustainability. Such studies introduced and demonstrated the integration of stakeholders and consultations at the community level for effective implementation of the WEF nexus leading to policymaking.

The studies by Daccache et al. (2014) and Daher and Mohtar (2015) were instrumental in the introduction of models for scenario planning for the WEF nexus. The two studies have a combination of direct citations Howarth and Monasterolo (2016), Sanders (2016), Mohtar and Lawford (2016), Garcia and You (2016), Kurian (2017), Kaddoura and El Khatib (2017), Hang et al. (2017), Berardy and Chester (2017), Miller-Robbie et al. (2017), and Zygourakis (2017). The 2016 research further illustrates the concepts of co-production, co-design and co-implementation for a successful WEF nexus. The studies indicated that the effectiveness of models lies in the understanding of nexus complexity, consideration of financial elements in the tools, recognition of the importance of multiple nexus approach directions, the incorporation of different time scales, and enhanced tool accessibility. Limitations identified included extensive data requirements of models and the poor synergy between models assessing individual nexus areas.

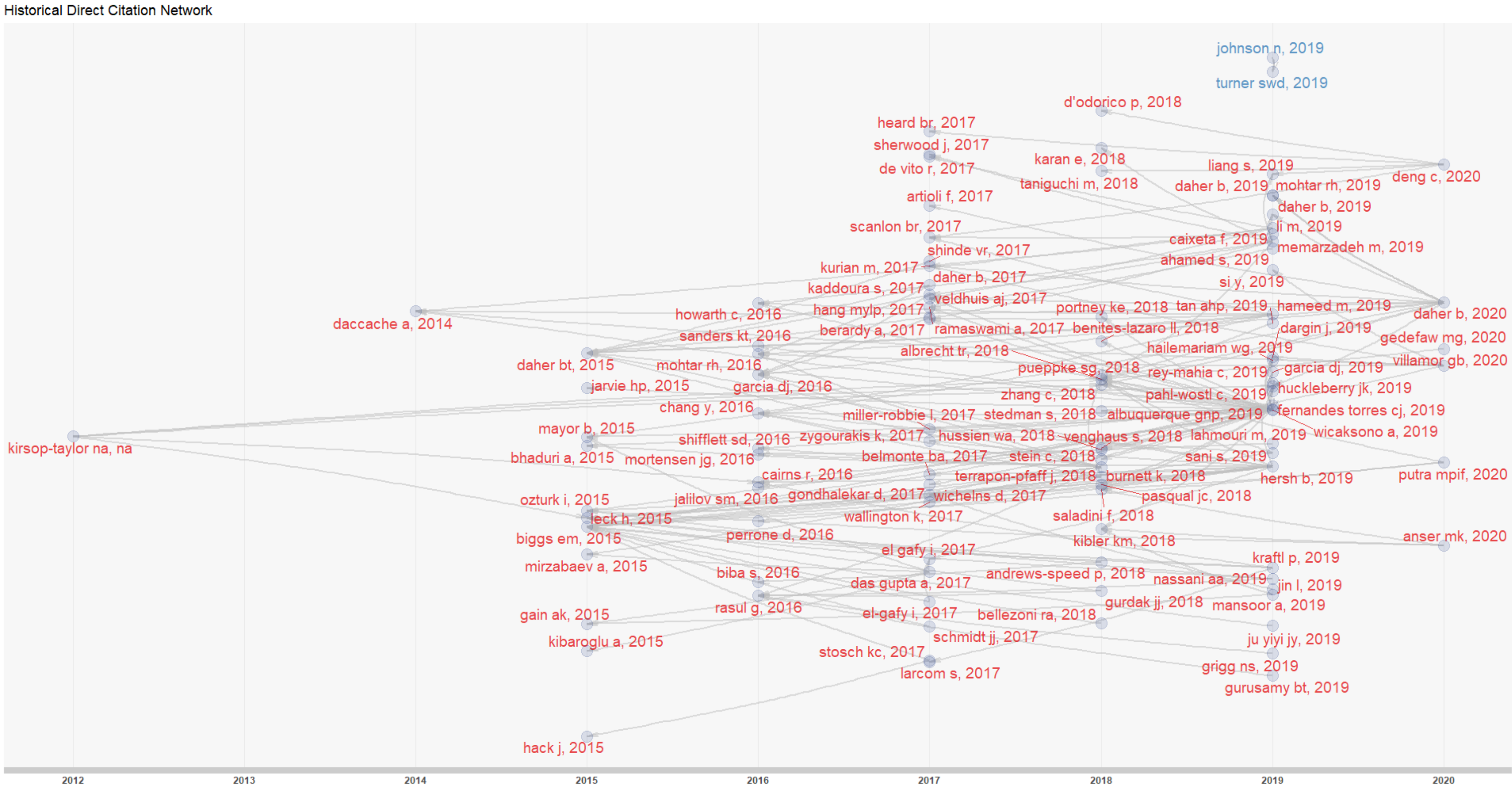

Figure 19. Historical direct citation network.

2.3.7. Discussion

The analysis above shows that research on the WEF nexus has been gaining traction in Africa since 2013. On a global scale, the need to understand this research trajectory has been linked to the WEF resource crises in 2008 and growing concerns to move away from sector-driven management strategies (Opejin et al., 2020). In Africa, the SADC region used the SADC 6th Multi-stakeholder Water Dialogue held in 2013 in Lusaka Zambia, in partnership with the Global Water Partnership Southern Africa, as one of the platforms to raise awareness and create shared understanding on the WEF nexus (SADC, 2013). The subsequent workshops in SADC also highlighted the knowledge gaps, stakeholders and their roles at various levels required to support the nexus in meeting the water, energy and food needs of the people and efficient use of resources to meet the SDGs (Mabhaudhi et al., 2018a).

In North Africa, initiatives such as the Arab League's Nexus Dialogue Programme and the Arab Coordination Group played a key role in the development of research and informed the development of policies that address WEF challenges. The WEF nexus research in North Africa has been driven by the growing demand for water, energy and food resources resulting from population growth, increased consumption, overexploitation of groundwater resources and the impacts of climate change (Adeel, 2017). In East and Central Africa, the transboundary basin of Lake Kivu and the Ruzizi River, which are shared by the Democratic Republic of the Congo (DRC), Rwanda and Burundi provides a wide range of ecosystem services and plays a key role in supporting the livelihoods of communities through fishing, irrigation water for agricultural activities and provision of non-timber forest products (Albrecht et al., 2018). The basin, however, has challenges resulting from unsustainable practices in agriculture, forestry, land use and water management, which are aggravated by climate change. Recent work in the Lake Kivu and the Ruzizi River basin by the GIZ in collaboration with the European Union and the Autorité du Bassin du Lac Kivu et de la Rivière Ruzizi (ABAKIR) seeks to understand the trade-offs between competing uses of water, land and energy, improve natural resource efficiency to sustain human livelihoods and ecosystem integrity in the basin using the WEF nexus approach.

In West and Central Africa, the WEF nexus has been driven by institutions such as the Niger Basin Nexus Dialogue, with the role being to advise and support the Niger Basin Authority (NBA) and its member states as well as to mainstream the WEF Nexus approach into the management of the basin. The WEF nexus has been pushed forth in the region to support integrated transboundary management of the basin and to design policies to holistically attain the development objectives by seeking efficiency of resources to address pressing developmental challenges such as food insecurity, poverty, unreliable rain, and high variable inter- and intra-annual river flows (Aboelnga et al., 2018a). In east Africa, research is still minimal but there have been initiatives by UNESCO in collaboration with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) gmbH, Strathmore University and the Kenya Climate Innovation Centre to highlight the interdependencies between water, energy and food in meeting global and regional goals such as the Agenda 63 (Rodriguez and Ferrini, 2019). The WEF nexus is expected to also address issues such as energy-efficient production, agriculture productivity, climate change, water management practices, the impact of global oil and food prices as well as the marginalization of the poor and refugees (Wakeford, 2017). In Tanzania, the WEF nexus has also been instigated to address hydropower-related issues, including the impact of the dam on downstream river flows.

The WEF nexus themes in Africa have shown a steady increase in publications that have been building on the work pioneered by Gulati et al. (2013) and Hanjra et al. (2013). Gulati et al. (2013) used the WEF nexus to interrogate how energy and water costs influence the price of food in South Africa and identified gaps in knowledge on the complex dynamics and dependencies of water, energy and food pricing. Studies by Hanjra et al. (2013) used the climate change risk for food security in Africa with a focus on agriculture as well as cross-cutting issues such as energy security, resource re-use and recovery, social protection programs, and involving civil society in food policy-making processes by promoting food sovereignty. From 2015, more research on themes focused on the linkages between WEF and green growth and neoliberalism, small-scale farmers, river basin, climate change, carbon stocks and flows (Keulertz and Woertz, 2015; Jobbins et al., 2015; Conway et al., 2015; King and Jaafar, 2015; Ozturk, 2015). The research had also expanded to other regions in Africa with regional research in North Africa (Egypt, Morocco, Tunisia, Lebanon, Algeria, Sudan), Southern Africa, BRICS and country-specific research in Morocco and South Africa. Only two nexus research outputs were produced in Africa in 2016 and the themes probed focused on the conservation of natural resources to support ecosystem health and adaptive governance through the WEF nexus on a continental scale (Gleeson et al., 2016). The research studies by Amos et al. (2016) were the first in Eastern Africa and specifically for Kenya that examine the socioeconomic benefits analysis of domestic rainwater harvesting in urban and peri-urban environments in the WEF nexus.

In 2017, about 11 publications were published in Africa with a focus on Sub-Saharan Africa, Southern Africa (Zambia and Mozambique), Eastern Africa (Djibouti and Somalia), West (Sierra Leone, Liberia, Guinea, Benin, Nigeria, Ghana and Burkina Faso) and Northern Africa (Egypt, Libya, Sudan and Morocco) (Endo et al., 2017; Hoffman et al., 2017; Zaman et al., 2017; Guta et al., 2017; Siciliano et al., 2017; Ololade et al., 2017; Zhang et al., 2018). New or developing themes in 2017 included the WEF nexus links to the charcoal value chain in Sub-Saharan Africa (Hoffman et al., 2017); WEF nexus and air pollutants in sub-Saharan Africa (Zaman et al., 2017); policy and WEF nexus on hydropower development in Africa; energy transition and the WEF Security

Nexus (Guta et al., 2017), WEF and regional security in Egypt, Tunisia, Libya, Sudan, Morocco, Djibouti, Somalia(Adeel, 2017). Siciliano and Urban (2017) draw from multiple case studies in Asia and Africa (Ghana and Nigeria) to highlight China's role as a rising power in low-carbon development specifically in hydropower. The study uses the WEF nexus to illustrate the political economy, political ecology and national priorities of energy production on one side, on the other side, it focuses on the local developmental needs resulting from unequal distribution and access to resources such as water, land and forest environmental and social justice particularly the compensation of communities as well as their access to natural resources.

Research with themes that fall under the basic or disappearing themes in 2017 includes research on agriculture, food supply and sustainable development. Ololade et al. (2017) examine how the interconnectedness, interdependencies, and security of food, energy, and water systems can lead to new policy paradigms and identify research needs for moving South Africa onto a sustainable development path. Ozturk (2017) uses pooled fixed effects, pooled random effects and pooled least squares regression techniques to demonstrate the dynamic nexus between water-energy-food (WEF) poverty and agricultural sustainability in selected sub-Saharan Africa countries. Siciliano et al. (2017) used the WEF nexus to inform European policies and regulations for the development of best practices on the presence of European large-scale farmland investments in the global South and their implications for the land-water-energy-food nexus. The study used case studies from multiple African countries, i.e. Zambia, Sierra Leone, Mozambique, Liberia, Guinea, Benin and Burkina Faso.

In 2018, about 12 publications were published focusing on Africa, Sub-Saharan Africa, SADC, West African countries, Eastern Africa (Tanzania), and Southern Africa (Udias et al., 2018; Nhamo et al., 2018; Mpandeli et al., 2018; Mabhaudhi et al., 2018a, 2018b; Antwi-Agyei et al., 2018; Pardoe et al., 2018; Yang et al., 2018; Dombrowsky and Hensengerth, 2018; Yang and Wi, 2018; Mwampamba et al., 2018; Udias et al., 2018; Seeliger et al., 2018; Matthews and Mccartney, 2018). Most of the research was built on some of the disappearing themes, for instance, Seeliger et al. (2018) considered the water, energy and agricultural food production nexus within the Breede River Catchment in South Africa, by demonstrating how the nexus approach, when embedded in a farm budget model, can contribute to understanding the relationship between water, energy and food as well as its effects on-farm profitability. The authors positioned the broad WEF nexus debate within the South African water sector and identified nexus links and efficient management alternatives to hypothetical agricultural scenarios (population growth, climate change) to increase system inputs. Research by other authors in southern Africa examined the status of irrigated agriculture within the SADC region from a WEF nexus perspective; explored how sector policies address the nexus; how to promote cross-sectoral policy linkage among WEF sector and how cross-sectoral linkages can facilitate coordinated action in Sub-Saharan Africa (Mabhaudhi et al., 2018b; Nhamo et al., 2018; Pardoe et al., 2018). Linked to new themes from 2017, that conceptualised the WEF nexus links to the charcoal value chain, Mwampamba et al. (2018) explored the interrelationships between charcoal, livestock, and hydrological processes. The study developed a theoretical framework to analyse where the interlinkages co-exist in Sub-Saharan Africa while also tapping on lessons from South-East Asia and Latin America.

Emerging themes in 2018 included research linking WEF and the environment (WEFE) focusing on the enhancement of food crop production in the transboundary river basin and implementation of E-Water, an open software Decision Support System (DSS), designed to help local managers assess the WEFE nexus in the Mekrou River Basin, shared among Benin, Burkina Faso and Niger in West Africa (Udias et al., 2018). Other emerging themes in 2018 include the linking of WEF resources to ecosystems, sanitation and dams while WEF and climate change were continuing themes from 2013 when the first work in Africa was done by Hanjra et al. (2013) but with a different focus. Mpandeli et al. (2018) for instance, linked WEF nexus resources and climate change focusing on how climate change impacts WEF resources at the international and regional levels within SADC. Antwi-Agyei et al. (2018) examined the WEF nexus in relation to sanitation, life on land and climate action with an emphasis on providing a better understanding of how Nationally Determined Contributions (NDCs) might facilitate SDGs progress in West Africa, particularly across goals 1 (no poverty), 2 (zero hunger), 6 (access to clean water and sanitation), 7 (affordable and clean energy), 13 (climate action) and 15 (life on land). The WEF nexus research in 2018 also interrogated the sustainability and trade-offs across the WEF ecosystem nexus in West Africa, and on WEF and ecosystems with special attention on water resources for agricultural production, energy generation, and ecosystem services in East Africa (Yang et al., 2018; Yang and Wi, 2018).

Yang and Wi (2018) developed a coupled modelling framework to quantify natural and human components that affect the WEF nexus in the Great Ruaha River system in Tanzania and adjusted the model based on the pooled calibration with multiple targets of streamflow, water depth, and hydropower generation. Matthews and Mccartney (2018) explored the synergies between the WEF nexus, dams and resilience by illustrating the challenges faced by decision-makers concerning building resilience and navigating risk within the WEF nexus and dam construction in Africa and Asia. The role played by regional organizations in governing hydropower also emerged as an important area related to WEF nexus impacts.

In 2019, continuing themes include interrelationships among water-energy-food resources, services and health sectors; livelihoods, health and human wellbeing and built onto the 2018 themes. Research in 2019 covered a wide range of regions in Africa including the work by Ding et al. (2019) which developed an analytical framework for evaluating the different interrelationships among WEF resources, services and health sectors in Sub-Saharan Africa with case studies in Senegal, Nigeria and South Africa. Mabhaudhi et al. (2019) adapted the WEF nexus analytical model developed by Nhamo et al. (2018) to develop a WEF nexus analytical livelihoods framework to assess and understand rural livelihoods, health, and wellbeing in southern Africa and recommend tailor-made adaptation strategies for the region to build resilient rural communities. Emerging themes in 2019 include synergies and trade-offs between water, food and energy in relation to water diplomacy, integrated natural resources management, transboundary sectoral agreements; coal mining as well as socioeconomic and political drivers of WEF.

Further research from 2019 compared and simulated the WEF system outcomes under different policy scenarios in South Africa, Cape Town, building on the already existing WEF theme (Ding et al., 2019), while Hameed (2019) explored socioeconomic and political drivers of WEF security in 16 Arab countries in the Middle East and from Africa, Egypt is one of the case study countries. The study carried out a comprehensive assessment to study and evaluate the emerging drivers of WEF systems in the region and investigated the drivers which include: water security, extreme events, economic growth, urbanisation, population growth, poverty, and political stability. Another area explored in 2019 was the crop-water management within a watershed in South Africa focusing on how observations on volumes of water used by a specific crop can improve the accuracy of water footprint calculations for products of that crop (Gush et al., 2019). The WEF and water diplomacy theme also emerged in 2019, with authors exploring the synergies and trade-offs among water, food and energy concerning water diplomacy, integrated natural resources management, and transboundary sectoral agreements in Eastern (Jordan) and Southern Africa (Zambezi River Basin) (Salmoral et al., 2019). The linkages of WEF nexus and coal mining involved the identification of interactions and trade-offs of WEF in Mpumalanga Province, South Africa. The authors did a critical review of the Mpumalanga Province through the lens of the WEF nexus by identifying and investigating interactions and trade-offs of WEF; analysing nexus interactions; drawing conclusions on the existing or potential threats to WEF security in the province as well as recommending potential corrective actions needed to remedy possible threats to the WEF security.

In 2020, the research focus to date has been on interlinkages among WEF resources in Southern Africa building on continuing themes. This includes South Africa from where an integrated analytical model was developed to simplify the intricate interlinkages among WEF resources (Nhamo et al., 2020a). In addition to this research, Laubscher and Cowan (2020) conducted a study to highlight the emerging nexus linkage between algae-based sewage treatment and energy production to emphasize the net energy that can be gained using an already substantiated integrated algal pond system and the value of its co-products that include water for recycling and re-use and an organic nitrogen-rich liquid fertilizer. Furthermore, the study investigated products desired by primary industries (e.g. agriculture and horticulture) in the peri-urban space, positioning algae-based sewage treatment within the WEF nexus and energy generation (Laubscher and Cowan, 2020). A summary of the regional nexus issues in Africa is shown in Table 3 below while further research in this project will focus on East and Southern Africa.

Table 3: Key nexus issues.

Region	Key Nexus issues
West Africa	• Sedimentation of in the Inner Niger Delta and the Marine Delta in Nigeria, • Social and environmental impacts of mining and oil extraction • Hydropower development to meet growing energy needs with the potential for about 30 000 GWH to be produced in the region (the region currently only produces 20% of this) • Addressing food security • The need to expand irrigation to enhance agricultural production • Navigation development to enhance commerce and development
Southern Africa	• Cross-sectoral policy linkage among WEF sectors. • Impact of climate change on WEF resources, at local and regional levels • Irrigated agriculture from the WEF perspective • Coordinated action through sector policies and cross-sectoral linkages • Analysis of interlinks between charcoal, livestock, and hydrological processes • Development of climate change adaption strategies in the region, which include: - - Promoting climate-smart agriculture - Developing early warning systems - Integrated water resource management - Promoting renewable energies with a low carbon footprint Increasing monitoring and modelling capacities across each of the WEF nexus.
Eastern Africa	• Coordinated action through sector policies and cross-sectoral linkages • Address the role of regional organizations in governing hydropower-related WEF nexus impact • Address nexus competition – water resources for agricultural production, energy generation, and ecosystem services Analysis of interlinks between charcoal, livestock, and hydrological processes

2.4. Practical Implications of WEF Nexus: How is the WEF Nexus put into Practice in Africa

2.4.1. WEF Nexus Implementation and Practical Implications

Despite the inadequate yet growing progress in the WEF nexus research as reflected in the publication output in the region (Figure 6), the WEF nexus frameworks are just beginning to be explored scientifically (Liu et al., 2017). As stated by Markantonis et al. (2019), the WEF nexus concept still needs to be appropriated beyond the theoretical domain. Its practical implementation on the ground remains a challenge due to a lack of adequate funding, skilled personnel, equipment and commitment from member countries (Liu et al., 2017; Nhamo et al., 2018; Markantonis et al., 2019). Furthermore, as indicated by Nhamo et al. (2018), there is a lack of indicators and metrics that play various roles highlighted in Marttunen et al. (2019) and when coupled with appropriate frameworks, these will lead to the WEF nexus implementation. Highlighted also is the lack of clarity on the spatial scale at which implementation should occur and how to quantify or assess such implementation (Nhamo et al., 2018). The absence of standardized procedures and methodologies to assist in the development and application of "nexus thinking" can also prevent implementation (Fernandes Torres et al., 2019). In the study by Voelker et al. (2019), the lack of institutional logic comes out strong as an impediment to WEF nexus implementation. Access to information systems and data from various observational platforms including satellite, in situ, models and assimilation systems, as well as socio-economic data, can also be a barrier to the implementation of the WEF nexus (Lawford, 2019). In addition, a lack of innovation may hinder the implementation of WEF nexus approaches (Hoolohan, 2018 and Mabhaudhi et al., 2018b) that allow for example the production of more food with less water and energy resources to help attain SDGs on poverty eradication, zero hunger, availing water to all, and provision of clean energy (goals 1, 2, 6, and 7 respectively). According to Hoolohan (2018), some innovative approaches offer benefits in all three nexus domains, addressing specific issues that each domain faces, as well as their overarching challenges.

An increasingly important barrier in the implementation of the WEF approach is the constraints in natural resource availability, distribution and access, predominantly in Africa where countries face the difficult task of sustainably meeting the growing demands for food, water, and energy, which is further compounded by climate change (Rasul and Sharma, 2015). The global water, energy and food demand are expected to increase in 2050 by 20% to 30%, 80%, and 60% respectively (Flammini et al., 2014; Burek et al., 2016). As expected, the demand will be much more significant in sub-Saharan Africa (van Ittersuma et al., 2016) due to rapid population growth, urbanisation and regional economics and socio-economic development. The lack of access to intrinsically connected systems is a significant constraint for sustainable development and can have negative implications on regional security to essential services needed to maintain and enhance livelihoods beyond generations.

2.4.2. Implementation and Cases of Wef Nexus in South and Eastern Africa

This section features some initiatives on the WEF nexus for South Africa and Kenya. The information is provided by the Water, Energy and Food Security Resource Platform (https://www.water-energy-food.org/). Since 2012, there has been a total of nine implementation case studies in Africa. The case studies are assessed for trade-offs and synergies and socio-economic and environmental benefits.

- **Return on the investment case study. Accelerating Solar Water Pump Sales in Kenya**

In Holthaus et al. (2017), food is one WEF element that is featured most prominently, and it contributed to the achievement of the SDG hunger goal. In the project, access to water for irrigation was addressed using renewable energy solar water pump systems that were purchased by local smallholder farmers. This initiative had the direct benefit of increased agricultural yield, with gross profits of up to 186%. Smallholder farmers were able to grow two or even three crops of high-value vegetables and fruits in a year. The choice of solar-powered pumps which are portable meant there is no land competition. Also, there was a reduction in the use of fossil fuel in the form of conventional diesel irrigation which also meant cost savings. Water and energy elements are also covered showing the interaction of the three WEF nexus elements.

- **Applying the Water-Energy-Food nexus approach to catalyse transformational change in Africa**

The Ikondo Matembwe project presented a WEF Nexus transformational approach to delivering renewable energy access, potable water and improved nutrition to rural communities in Tanzania. The implementation of the project had a beneficial and lasting transformation in the socio-economic framework of the communities with environmental advantages for the town, which justify the project's implementation as well as technological replicability in some other similar places.

- **Informing regional Water-Energy-Food nexus with system analysis and interactive visualization. A Case Study in the Great Ruaha River of Tanzania**

Yang and Wi (2017) examine the use of water resources in the Great Ruaha River of Tanzania. Water resources in this area are constrained and subject to competing usages, including ecosystem services, energy generation, and agricultural production. In this case study, the coupled human-nature interactions in the Great Ruaha River basin were simulated, making use of an innovative water method modelling strategy. The findings were visualised through active web-based resources (Data Driven Document, D3) which foster a fuller understanding of the findings for both practitioners as well as stakeholders. The study revealed that the mixture of advancements in irrigation effectiveness, cutbacks on the proposed expansion of irrigated lands, along with a low head weir at the wetland outlet, drastically lowers the amount of 0 flow days resulting in positive effects on the agricultural sector. In addition, the measures freed water resources to use in hydropower production in the area**.**

- **Science Forum 2018 Case Study. Examining trade-offs in the allocation of biomass energy sources to domestic and productive uses in Ethiopia**

In Mekonnen et al. (2018), the trade-off between the usage for domestic cooking as well as heating purposes, rather than leaving the biomass in the area to correct soil organic matter was examined, that is energy and food nexus. The results indicate that the use of biomass as a domestic energy supply has decreased farm productivity in Ethiopia since organic matter is being taken out of the agricultural fields to fulfil home energy demand. Farm households, particularly girls and women, spend a rather considerable number of hours a week in search of fuelwood to satisfy domestic power demand, a period that might have been utilised in other productivity-enhancing pursuits. The use of fuelwood was considered the best option for domestic energy supply since it does not affect agricultural output, thus leading to sustained and efficient food production.

- **Water-Food-Energy-Environment synergies and trade-offs. Major Issues and case studies**

Hellegers et al. (2008) used both a brief global overview as well as a closer review of four case studies from India, Ethiopia, Jordon and the USA. The paper presents the WEF nexus trade-off by evaluating the interrelationships between water, food, and energy. Soaring fuel costs and the effects of climate change are reviving policymakers' interest in renewable energy sources, including hydropower and bioenergy. The development of energy sources have the potential to produce good economic return as well as environmental benefits, but, at the same time, they might affect agricultural production due to the use of water and biomass for energy. This entails significant trade-offs between food, water as well as energy development, management and allocation.

- **MAXUS. Synergizing water, food and energy policy**

In studies by Burger (2018), the 'MAXUS" model was applied to a case study in Ghana and Burkina Faso. MAXUS model optimises one or more objective functions of the WEF nexus study. This functionality makes it possible to apply the models to different WEF elements and different countries as is the case in this study. The model demonstrates the interdependencies of the WEF elements where a decision taken in one WEF nexus element will have a direct implication for the other WEF elements. In the study, the electricity demand increase caused agriculture to respond by moving the production of different crops to different locations. Water allocation was adapted accordingly.

- **(GIZ and ICLEI, 2014): The urban nexus. Demonstrating the urban nexus approach to link water, energy and food resources in schools in Tanzania**

This particular undertaking aimed to showcase a multi-departmental Urban NEXUS Growth Cycle method for the planning as well as implementation of school infrastructure as well as services to showcase efficiencies as well as cost savings. This project was conducted in compact two high-density schools located in low-income communities in Dar es Salaam. The case study highlighted gains with the application of the Urbanized NEXUS approach that linked water, energy, urban agriculture and nutrition with waste, health and education for enhanced productivity and quality of life. The school started two food gardens to feed poor schoolchildren. In addition, with the assistance of local communities harvesting rainwater and developing efficient fuel stoves.

- **(World Bank, 2017): Modelling the water-energy nexus: how do water constraints affect energy planning in South Africa?**

In this study, the South African Integrated MARKAL-EFOM system (TIMES) model (SATIM) developed by the University of Cape Town was used as a tool to evaluate the water and energy WEF nexus, a case study for South Africa and as a predominantly arid country, faced with the challenge of water scarcity. While the country has abundant coal supplies, it faces electricity supply challenges. This case study focuses on including a representation of water resource infrastructure expenses to an energy supply to better mirror the interdependent dynamics of the energy-water nexus in South Africa as well as the water supply problems facing the country. The outcomes of this investigation show the task as well as the kind of equipment that may be used to look at the energy-water nexus in a national-level planning context, as well as the insights which can be acquired from water-smart power preparation. Several pertinent policy scenarios in South Africa had been explored, as well as the results showing that certain power sector policies can have considerable implications for both new investment in water source infrastructure and several cases can result in stranded power as well as water investments, reinforcing the benefits of preparing these sectors by way of a nexus strategy.

- **Water for Food, Energy and Ecosystems. Case of the Inner Niger Delta, Mali**

The promotion of food security is the top concern of the Malian Government. This had led to an increase in agricultural production which has resulted in more demand for the scarce water resources extracted from the Niger River and at the same time water is required for the booming hydropower electricity production. The increasing competition for water has indirect and direct impacts on changing the water regimes leading to trade-offs of various water management scenarios like the impacts for all stakeholders in the catchment.

2.5. Gaps and Recommendations for Future Work

From the inception of WEF nexus research in Africa in 2013, several gaps and/or recommendations have been identified. Many of these gaps have been addressed in subsequent studies. However, the following gaps have not been implemented.

- The implementation of trade-offs among the WEF nexus for sustainability that include food-water-energy security in alignment with the SDGs
- The need for scenario planning within the WEF nexus to incorporate

- sector-specific issues
- gender mainstreaming
- poverty and inequality

- Inclusion of stakeholders that include politicians, policymakers, and grassroots/indigenous people for co-development, co-design methodology
- Integration of modelling systems.

The responses to these gaps will improve understanding of how the WEF nexus interact with other components of the socio-political and socio-economic system.

2.6. Concluding Remarks

The bibliometric analysis approach was adopted in this report to examine the current trends, opportunities and gaps in water, energy and food nexus research in Africa, with a particular focus on the eastern and southern African regions. This review study was based on an analysis of associated research articles on WEF nexus research published globally and in Africa between 2012 and 2020. Current literature shows that in Africa, six main WEF themes have been the foci of research that examined WEF linkages to water resources, water supply, resources management, decision making and climate change. Whilst there is significant research conducted that has been done on the themes above in Africa, in general, there are three key emerging themes that the WEF nexus research should pursue in Southern and Eastern Africa. Firstly, there is a need for further research to explore how the WEF nexus can support the transition towards a sustainable development pathway as well as influence policy pathways to address some of the key developmental challenges in Africa such as poverty, water scarcity, and food and energy insecurity. Secondly, WEF nexus there is a need to improve understanding of how the WEF nexus can support food production and supply including strengthening the capacity of smallholder farmers to increase productivity and resilience to shocks and stressors such as climate variability and economic instability. The last emerging theme that needs to be interrogated further in Eastern and Southern Africa is water management particularly given the increasing competition for water and the projections of increased temperatures and drying in parts of these two regions which will result in increased demand for the scarce resource. More so, there is a need for nexus research to enhance policies and coordinated governance of water resources in transboundary basins to ensure sustainability. In addition, the literature review has identified several issues that constrain the mainstreaming or achievement of trade-offs, compromises, or synergies in the resolution of the competition between the nexus elements and these include institutional and policy silos; national and development partner institutional arrangements that do not favour integrated systems thinking; limited technical capacity; rigid development plans and power relationships between national institutions and transboundary interests. Consequently, there is, therefore, a need to address these issues through regional solutions to local problems whilst also considering the comparative productive advantage of investments across the nexus value chains that expand and diversify livelihoods.

3. AN APPLICABLE AND SCALABLE WEF NEXUS MODEL

3.1. Introduction

Water, energy, and food security are intertwined issues that threaten environmental, economic, and social sustainability, and in the light of persisting inequalities, the availability and sustainable access or provision of these resources have become increasingly constrained (Wakeford, 2017; Purwanto et al., 2019; Okumu et al., 2021). Currently, 2 billion people lack regular access to nutritious and sufficient food, 1.5 billion have no source of electricity, 3 billion are without access to clean fuels or technologies for cooking, and lastly, 785 million people have no access to safe water (Schlör et al., 2018; WHO, 2019a; WHO, 2019b). These deficiencies are anticipated to worsen as the world's population expands to 1 billion people by 2030 (United Nations, 2015). As Schlör et al. (2018) pointed out, by 2030, global water demands are expected to grow by 30 to 40%, demand for energy by 40 to 50%, and demand for food by 35 to 50%, leading to greater shortage and eventually exhaustion of supply. The Southern and Eastern regions of Africa are not immune to these observed challenges. For example, it has been reported by Mabhaudhi et al. (2019), that approximately 60% of Southern Africa's population lives in rural regions with inadequate access to essential services and utilities such as safe and clean water, affordable and clean electricity, and balanced and healthy meals. For East African countries, vulnerabilities arise from endemic circumstances, such as insufficient access to water, electricity, and food, as well as from unique risks posed by external threats such as climatic variability and oil and food price shocks (Wakeford, 2017).

The collective scientific literature reveals that water, energy, and food access is fundamental not only for securing basic human rights and dignities but also are central to the global sustainability challenges, thus necessitating the need to plan, manage and allocate the available resources in a sustainable and integrated manner (Mabhaudhi et al., 2019; Nhamo et al., 2020a; Botai et al., 2021). The interdependence and interlinkages of the three sectors are referred to as the Water-Energy-Food (WEF) nexus, an integrated approach that balances trade-offs and synergies in resource management and planning. Through this approach, the water, energy and food systems are inherently interlinked and are considered equitable without compromising the resource base of either of the sectors (Hoff, 2011). A shift from the conventional approaches to the WEF nexus concept will enhance resource security and sustainable development, thus addressing related policy challenges that are urgently needed (Botai et al., 2021; Naidoo et al., 2021). However, in the absence of a holistic systems-thinking transition, the WEF demands will continue to grow as driven by climatic, environmental, and continuous socio-economic demographic changes such as population growth, migration, and regional economics, which in turn alters the availability and accessibility of water, energy, and food resources (Markantonis et al., 2019). Furthermore, human-development-related

Sustainable Development Goals (SDGs) of zero hunger (SDG 2), clean water and sanitation (SDG 6) and affordable and clean energy (SDG 7) will not be reached (Moyer and Hedden,2020).

Undoubtedly, as captured in Albrecht et al. (2018), the WEF nexus approach will aid efforts toward (1) resource efficiency, (2) policy integration, (3) sustainability, (4) economic efficiency, (5) adaptation and resilience, (6) human and resource security and (7) environment and ecosystem. An example of a conceptual framework that focused on nexus linkages as they related to WEF security is depicted in Figure 20. Overall, the adoption of the nexus framework will improve decision-making and support local communities as well as improve their resilience despite socio-economic and environmental complexities, challenges, and constraints.

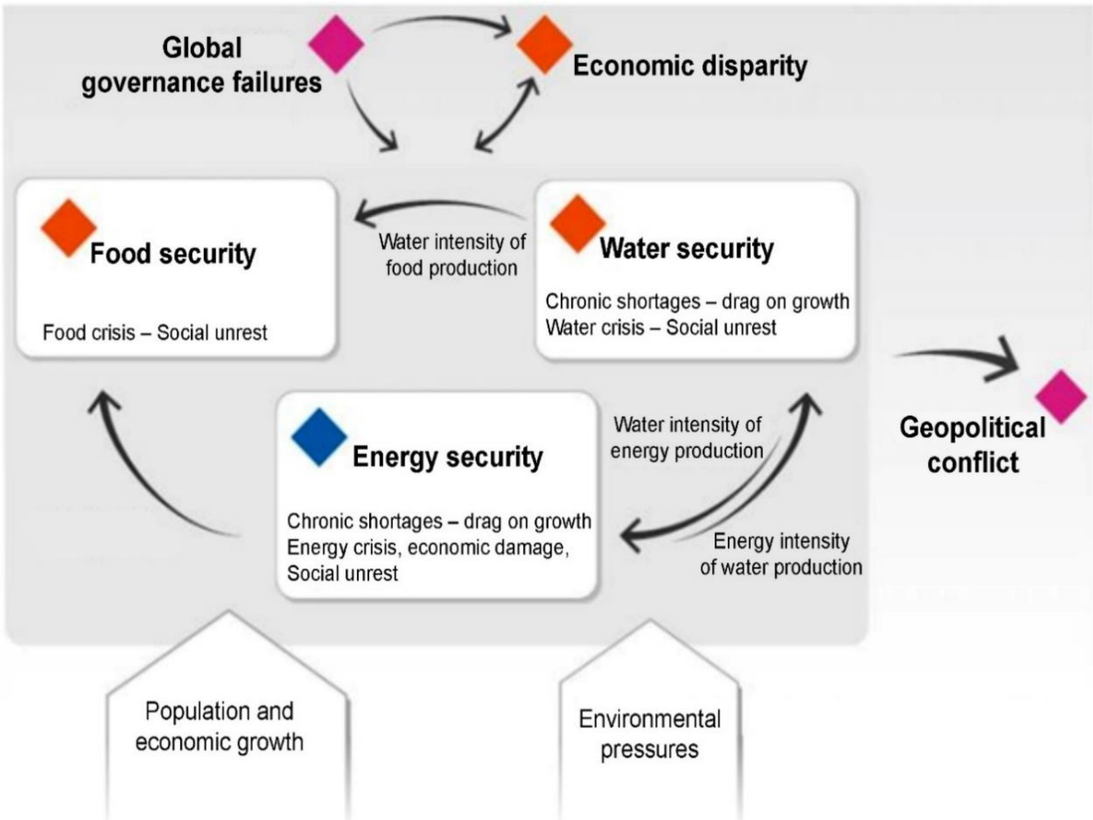

Figure 20: Water-Energy-Food Security Nexus from World Economic Forum. *Source: World Economic Forum (2011)*.

Because of the unique characteristics and complexities of the WEF nexus, such as resource constraints and dynamics between multiple stakeholders, there is no well-established technique for practising and implementing the nexus approach; hence various WEF models and frameworks have been developed in the quest to evaluate and understand the connections and interdependencies between water, energy, and food systems (Bijl et al., 2018; Shannak et al., 2018). The modelling frameworks or tools can be conceptual (qualitative), quantitative, and some combination of both qualitative and quantitative (Purwanto et al., 2019). Additionally, they can be applied at different spatial scales, ranging from national (Youssfi et al., 2020; Nhamo et al., 2020b), provincial (Simpson et al., 2019) to household scale (Hussien et al., 2017). Various modelling frameworks on the WEF nexus have been developed, below is a list of a selected few.

1. The Water-Energy-food Nexus tool 2.0 evaluate different scenarios and studies sustainable resource allocation strategies in Qatar (Daher and Mohtar, 2015),
2. The Water, Hydro-power, Agriculture Tool for Investment and Financing (WHAT-IF) tool for water infrastructure investments planning (Payet-Burin et al., 2019),
3. A qualitative Karawang WEF security (K-WEFS) model based on six sub-models with water, energy, and food sectors as endogenous factors (Purwanto et al., 2021), and
4. Nhamo et al. (2020a) identified WEF nexus sustainability indicators and integrated them using the Analytic Hierarchy Process (AHP) and the Multi-criteria Decision-making Approach to integrate and establish numerical relationships among WEF sectors.
5. Wen et al. (2022) conceptualised and developed a feedback model for the WEF nexus from a Resourced-Based Regions' (RBRs) perspective using a system dynamics approach. The RBRs WEF nexus model considered the WEF nexus system from both the supply and demand sides while also classifying WEF resources.

Several critical review studies have provided in-depth analyses of the various WEF models and frameworks developed over the years (Shannak et al., 2018; Albrecht et al., 2018; Endo et al., 2020; Shivakumar et al., 2021). These reviews have revealed the best practices and advances in WEF nexus assessment tools, yet, deficiencies and limitations in the applied methodologies have also been brought to the fore. Aspects such as incorporating the dynamic context of local conditions, addressing complex relationships, and interactions and feedback among water, energy, and food sectors have also limited the implementation of some of these models. Currently, there is no consensus on the best WEF model or framework hence the need for further development of nexus methodologies and tools based on local conditions and outcomes which will be usable and accessible by policy and decision-makers at the local level (IRENA, 2015; Byers, 2015; Leck et al., 2015). To this end, this deliverable focuses on the development of the WEF nexus framework based on the available data sets in South Africa and Kenya. The proposed model is expected to be all-inclusive and multiscale, which is useful in defining and quantifying the interconnectivity between water, energy, and food resources available at selected sites and supporting the development of an integrative strategy for complete future resources' management planning.

3.2. Methodology

3.2.1 Water-Energy-Food Nexus Assessment Approach

As illustrated in Figure 21, the WEF nexus resource analysis for Vhembe District Municipality and Narok County is based on a two-step qualitative assessment methodology adopted by de Strasser et al. (2016) and Karnib (2017). The collected information will be used to develop an integrated composite index that will support decision-making related to water, energy, and food inter-relationships at the two study sites.

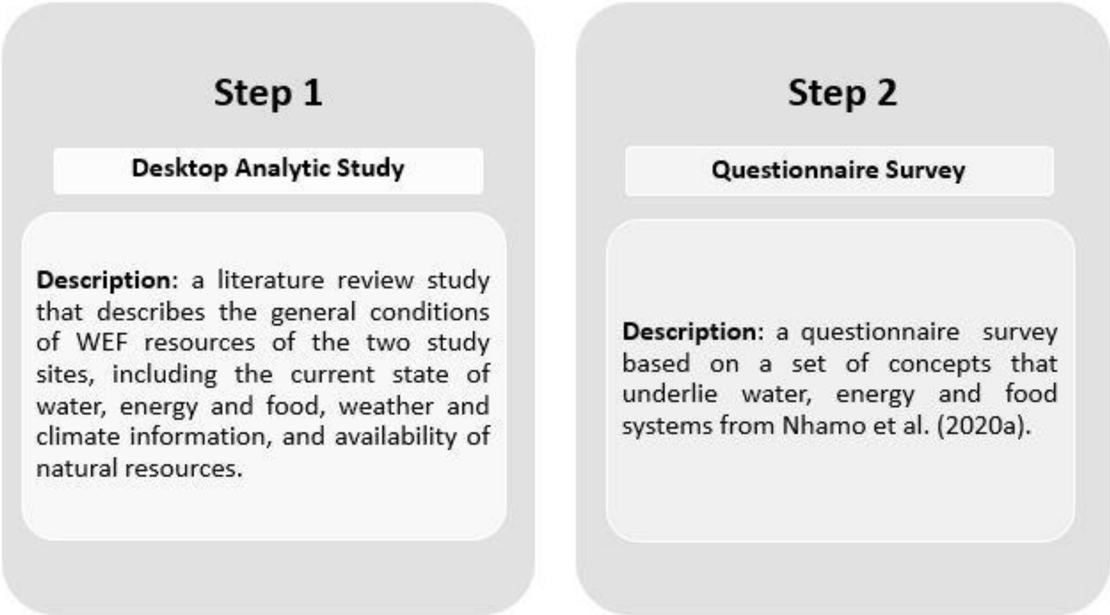

Figure 21: A two-step methodology for Water-Energy-Food nexus assessment for Vhembe district municipality and Narok County.

3.2.1.1. Step 1: A Desktop Analysis of Key Sectors

The State of Water-Energy-Food Nexus Resources in the Vhembe District Municipality

The LRB is home to over 14 million people who live and depend on the riparian zones of Botswana, Mozambique, South Africa, and Zimbabwe. For this study, the WEF nexus modelling framework will be applied in Vhembe District Municipality, located in Limpopo Province, in the Northern part of South Africa. The Vhembe district in the extreme northern part of the province receives an average annual rainfall between 300-400 mm, and most of the water is lost due to high evaporation rates (Mpandeli et al., 2015) hence the district is characterized by frequent occurrences of drought events (Mpandeli and Maponya, 2013; Mosase and Ahiablame, 2018). The mean annual temperature ranges from 9 to 17°C during winter and 22-37°C during summer. In terms of demographics, the population increased by 0.8% from 1 294 722 in Census 2011 to 1 393 949 in 2016 (StatsSA, 2016).

Generally, the rural areas of South Africa are vulnerable to water shortages, and the Vhembe District Municipality is no exception, with limited access to reliable water resources and the communities rely on unclean open sources such as rivers and dams as well as groundwater resources (VDM, 2012). According to Jaka (2019), the Limpopo Province has four water management catchment areas, namely, Limpopo, Olifants, Luvuvhu-Letaba, and Crocodile West Marico. The Luvuvhu-Letaba is the primary catchment for the Vhembe District Municipality. Other water resources include 12 dams, 3 weirs, and 38521 boreholes for access to groundwater (Jaka, 2019). The water supply that mainly comes from dams, rivers, and boreholes is inadequate as some dams are over-allocated or have no allocation for domestic use (e.g. Nzhelele dam). Drying up groundwater sources and pollution have been reported in Masisi communities (VDM, 2019). Additionally, the expansion of mining activities that use a large proportion of the water in the municipality further threatens water security. The Vhembe District Municipality suffers from poor water quality and drying up of groundwater, funding, maintenance, theft, and vandalism. Notably, the number of boreholes in the district seems high. However, they are unequally distributed across the municipal areas (Makhado has 23165, Thulamela 7871, Musina 1170, and Mutale 3057) (Jaka, 2019). The district thus has a relatively limited supply of both ground and surface water and is consequently stressed by the high demand for water for various activities, including agriculture, human consumption, and mining. Water management in the district faces the following challenges: an imbalance between the supply and demand for water, alien invasion, inappropriate land uses in the river valleys, the impact of fertilizers and pesticides, inadequate monitoring, poorly managed sewage systems, high concentrations of pit latrines, flood events and droughts.

The Vhembe District Municipality is mandated to increase the accessibility of clean, efficient, and reliable energy for all. From a total of 296 000 households in the district, only 196 000 households have access to electricity. The rest of the households rely on wood since it is cheaper than other sources. According to Jaka (2019), the choice of fuel in Vhembe is influenced by household income, with the preferred energy sources being electricity or gas. A survey conducted by StatsSA (2016) on energy sources and access indicated inequalities among the districts. In this survey, they looked at houses with conventional meters (prepaid), households connected to other sources (paying), households connected to other sources (not paying), generators (other), and no access to electricity. Results showed that most households (93,74%) in the Vhembe District Municipality have access to electricity, whereas a low number of approximately 4,06% have no access. It was established that Thulamela (32,79%) and Makhado (28,84%) local municipalities have a high number of people with access to electricity using prepaid. Meanwhile, Musina and Collins Chabane have the highest percentages of non-paying residents connected to other sources at 0,32% and 0,21% respectively. Also, Musina and Makhado have the highest proportion of connected and paying residents. Overall, the Vhembe District Municipality showed diversity and inequality in electricity access. Feasibility studies conducted in the district indicated that the municipality has the potential for alternative energy in the form of biogas which can be used to meet the current energy needs of poor households. Vhembe has been collaborating with the Eskom, University of Venda, Gondal/CLGH to support bioenergy and manufacturing of solar power as part of their green economy initiatives (VDM, 2019).

The food sector is a major user of water and energy. South Africa is rated food secure, but most rural areas struggle with food accessibility. South Africa aims to achieve food availability for all in sufficient quantities and promote pricing policies to make food affordable. People in rural areas are primarily dependent on farming as their main livelihood activity. Approximately 75% of the income of rural households is derived from small-scale farming under rain-fed agriculture, insufficient resources, and the impact of climate variability and change (Mabhaudhi et al., 2019). In the Vhembe district, the majority of the population relies on rain-fed agriculture for their livelihoods (Kom et al., 2020). The agricultural system includes large-scale commercial farming and small-scale farming. Fruit farming includes citrus, avocado, macadamia, mango, banana, litchi, and garlic farming, while crop farming includes maize. De Cock et al. (2013) declared that 53% of rural households in Limpopo Province are severely food insecure. Food insecurity is caused by increasing food prices, fuel and energy, political instability, economic instability, and environmental degradation. Limited work has been published on food resources in the Vhembe District Municipality.

The agricultural sector activities have therefore resulted in over-exploitation of surface and groundwater for irrigation, e.g. in the Sand catchment, Nzhelele catchment, Mogalakwena River as well as the Albasini Dam (VDM, 2021). The Vhembe District Municipality IDP reported that developments in rural areas had been constrained by the land tenure system, limited access to business opportunities, high agricultural input costs, the lack of mechanized agriculture, and disease outbreaks. Some food security studies in Limpopo Province in Jaka (2019) looked at food security with a particular focus on food expenditure, hunger, and household production. In terms of food poverty, 905 880 (70%) of the population in the district live under the food poverty line. Most rural households in Vhembe plant crops in backyard gardens. In Limpopo, approximately 92% of households resort to agriculture to supplement their existing sources of food (VDM, 2012). An estimated 53% of the population in Limpopo is poor and hungry (De Cock et al., 2013). Not all Vhembe district communities can have gardens in the backyard. Some areas in the Vhembe district are not suitable for farming, and the absence of fertile soil forces the community to rely on purchasing food. However, because of low income, people in the area resort to buying cheaper food products that are mainly processed and lack nutrients. These products have a considerable impact on the community's overall health and well-being (VDM, 2012, Mabhaudhi et al., 2019). Table 4 summarizes the WEF resources available in the Vhembe District Municipality.

Table 4: Summary of WEF resources in Vhembe District Municipality.

Sector	WEF nexus resources
Water (Nesamvuni, 2022)	Surface water (55,4%), groundwater (44,2%), missing system (0,4%)
Energy (Rasimphi and Tinarwo, 2020)	Wood (63%), electricity (34%), gas (2%), paraffin (1%)
Food (Oni, 2010)	Vegetable garden (32%, fruits (20,6), crops (20,6%), poultry (11%), fishery (4,7%), piggery (3,2%), cattle (7,9%)

The State of Water-Energy-Food Nexus Resources in Narok County

In Kenya, the selected study site is in Narok County in southwestern Kenya. The project focuses on some parts of the Mau Forest Catchment Basin (MFCB), which includes the Mau Water Tower (also known as the Mau Forest or Mau Forest Complex). The Mau Water Tower, which is one of the five largest water towers in Kenya, supports agriculture, tourism, and hydro energy production (Odawa and Sewo, 2019). In terms of water supply, the catchment provides several main rivers with water, including the Mara River, Sondu Miriu, Southern Ewaso Nyiro, Nzoia, Kerio, and Sondu Miriu, which flow into Lake Victoria, and some into Lake Natron and Nakuru. The quality and quantity of water in the Mau Forest Water tower has declined due to rapid population growth in the area resulting in land-use change and cover as well as loss of biodiversity as evidenced by a sharp increase in the area covered by grassland and severe decline in forest cover which enhances the water tower's ability to replenish springs and rivers (KWTA, 2015). Narok County is one of the rural counties in Kenya (Asige and Omuse, 2022). The average temperatures range from a minimum of 8˚C to a maximum of 28˚C and the County has two rainy seasons with short rains averaging 500 mm, and long rains averaging 1800 mm per annum (Korir and Ngenoh, 2019).

Approximately 252 880 hectares of Narok County's land are used for crops like wheat, barley, maize, beans, sugarcane, Irish potatoes, finger millet, pigeon peas, cowpeas, sweet potatoes, and cassava, and horticultural crops like tomatoes, potatoes, cabbage, French beans, onions, and indigenous vegetables. Farmers also keep dairy cows and poultry for subsistence (MoALFC, 2021). The main activities thus include small- and large-scale farming such as livestock rearing, maize and sorghum production, tea plantations, and dairy farming. Most farmers in Narok County work without basic agricultural inputs or modernized technology and lack adequate financial and extension services to promote sustainable production (Lawrence and Rotich, 2021). In Narok County, climate change hazards such as droughts and floods are becoming more frequent, more severe, and less predictable (Korir and Ngenoh, 2019). Furthermore, the population of Narok increased from 299 319 in 1979 to 850 920 in 2009, and the catchment has been experiencing a decline in riparian vegetation, loss of soil, and clearing of forests to expand human settlements as well as conversion to cropland (Matano et al., 2015; Odawa and Seo, 2019). Additionally, the energy supply is mainly from hydro-power plants, the Sondu-Miriu hydro-power plant on the Sondu River, and the catchment, in general, is estimated to have the capacity to produce 40% of Kenya's current generation capacity (UNEP, 2013). Forests have also been cleared for firewood as a primary source of fuel for cooking and logging. Efforts are being made by government agencies to support the reforestation and delineation of extremely critical water catchments and biodiversity hotspots for conservation (Njue et al., 2016). Table 5 summarises WEF resources in Narok County.

Table 5: Summary of WEF nexus resources in Narok County.

Sector	WEF nexus resources
Water (Pegasys Institute report, 2015-2016, Wakeford, 2017)	Surface water, groundwater and Aquifer
Energy (Wakeford, 2017)	Biofuel and waste (71%), oil products (22%), coal (2%) and electricity (5%)
Food (Lawrence and Rotich (2021).)	Crop (e.g. maize 52%; beans 8%, wheat 27%; potatoes 13%), Livestock (e.g. cattle, chicken, goats, pigs and sheep)

Water-Energy-Food Nexus Resources Interdependencies

The interdependence among the WEF nexus resources within both regions is such that water is required to produce energy, and energy is required for the extraction, distribution, and treatment of water, while both energy and water are essential for food production. Table *6* shows the local matrix, while the interlinkages are shown in Figure 22.

Table 6: Local WEF Nexus Matrix.

	Water	Energy	Food
Water	• Efficient irrigation technologies can save water • Water treatment • Wastewater treatment • Water desalination	• Energy used for clean drinking water • Increased water availability (groundwater pumping) • Wastewater treatment • Energy used for irrigation • Energy-efficient irrigation technologies can save energy • Cooling systems of geothermal and nuclear power plants • Hydroelectric power generation • Fossil fuel production	• The use of biomass waste for energy can reduce water pollution • Incorrect handling of biogas effluents can pollute water sources • Water for sanitation • Irrigation • Food processing
Energy	• Water used for energy generation • Water used for energy can alter water flows, which can result in environmental impacts	• Energy used for lighting or other electrical appliances (TV, mobile phone, machinery, etc.) • Reduced usage of unsustainable fuel sources (e.g. kerosene, diesel)	• Feedstock for bioenergy generation • Fertilizer preparation • Agricultural machinery • Transportation

	Water	Energy	Food
	• Water used for energy can reduce water availability for other uses • Groundwater pumping • Water treatment and distribution	• Heat for geothermal power plants • Fuel for the extraction processes	• Cooling systems for food storage • Food processing
Food	• Improved irrigation can increase agricultural production • Sustainable agricultural practices can reduce water pollution and water use • Crop production may lead to water pollution • Crop production	• Food processing and preservation • Agricultural processing • Reduced pressure on the environmental system due to reduced fuelwood use • Bioenergy crops compete for land with food crops • Farm mechanisation • Bioenergy and biofuel production	• Sustainable agricultural practices supported under the framework of • Sustainable energy projects • Animal feed

The continuously growing demand for water, food, and energy inherently increases the competition over resources, making it difficult to ensure the availability and security of all three resources. The security aspect of the WEF nexus components may be considered as the difference between supply and demand. For instance, both groundwater resources and surface water, including water returning from wastewater and agriculture are important components of the water supply system, which is decreased by the water demand. The water demand constitutes various components, including the urban and rural water demand which are linked to population growth and per capita water consumption. The same applies to the energy sector water demand, the agricultural sector (food and animal) water demand, and the industrial/municipal demand for water.

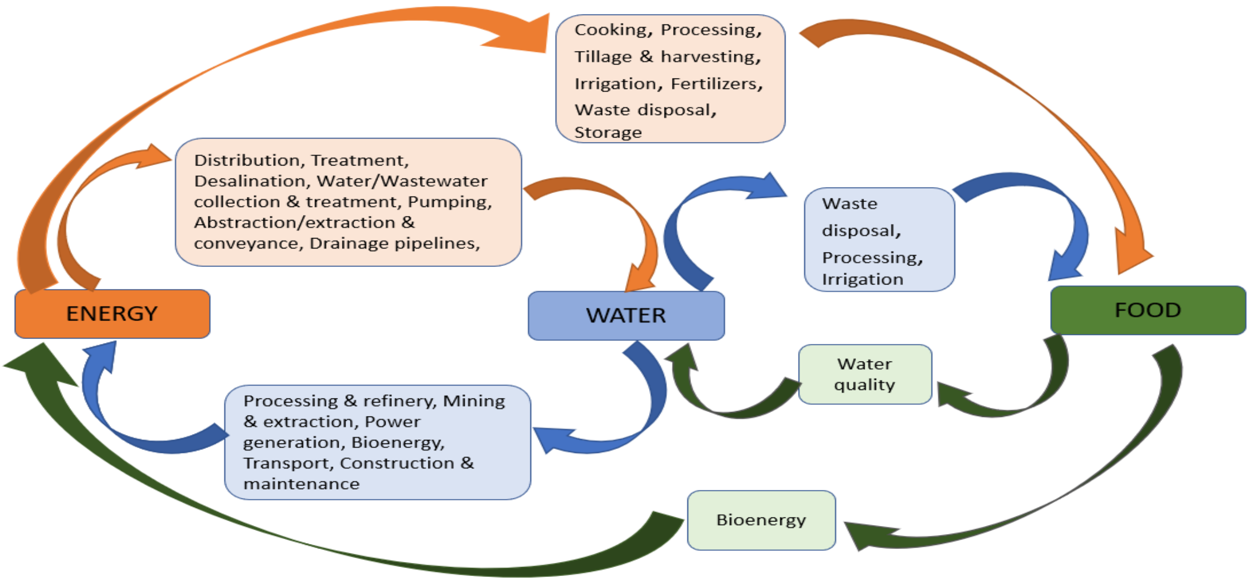

Figure 22: Water-Energy-Food nexus resources interlinkages

3.2.1.2. Step 2: Questionnaire Survey

An online survey was developed and circulated to industry experts at the two study sites, however, the response rate was low; hence the analysis could only be done for Vhembe District Municipality. The online survey questions were based on the six WEF nexus indicators described in Nhamo et al. (2020a). Questionnaires are widely regarded as viable data-gathering tools in sociocultural valuing studies (Scholte et al., 2015), hence their use in this assessment. The data gathered comprised of: (i) the availability and productivity of water resources, (ii) accessibility and productivity of energy resources, and (iii) self-sufficiency and productivity of food resources, these are considered drivers of water, energy, and food security (Mabhaudhi et al., 2019). Table *7* defines the WEF nexus sustainability indicators considered in determining the WEF nexus integrated composite indices (Nhamo et al., 2020a). Data analysis was conducted in EXCEL® and the package "ahpsurvey" (Cho, 2019) in R version 4.1.2 (R Core Team, 2020). The "ahpsurvey" package provides a standard technique for researchers to reformat data and run the Analytic Hierarchy Process (AHP) developed by Saaty (1987).

Table 7: WEF indicators based on Nhamo et al. (2020a).

Sector	Indicators
Water	Proportion of available freshwater resources per capita *(availability)* m3/capita
	Proportion of crops produced per unit of water used *(productivity)*
Energy	Proportion of the population with access to electricity *(accessibility)*
	Energy intensity measured in terms of primary energy and GDP *(productivity)*
Food	Prevalence of moderate or severe food insecurity in the population *(self-sufficiency)*
	Proportion of sustainable agricultural production per unit area *(cereal productivity)*

3.2.2. Computation of Water-Energy-Food Nexus

The integrative Water-Energy-Food Nexus Analytical (iWEF) model originally developed by Nhamo et al. (2020a) was used to determine the relationship among WEF nexus components. The iWEF tool integrates the six WEF nexus indicators (Table 7) through the Analytic Hierarchy Process (AHP) Multi-Criteria Decision-Making (MCDM) approach. The AHP, which is an MCDM approach, was utilised to integrate and build numerical correlations among the WEF nexus indicators and calculate indices. As captured in Mabhaudhi et al. (2019) and Nhamo et al. (2020b), the AHP comparison matrix is calculated by comparing two indicators at a time using Saaty's scale (Saaty, 1977), which spans from 1/9 to 9. A range of one to nine signifies a significant connection, whereas a range of 1/3 to 1/9 represents a minor relationship. A score of nine implies that the row element is nine times more significant than the column factor. A grade of 1/9, on the other hand, suggests that the row indication is 1/9 less relevant than the column indicator. When both the column and row indications are equally important, they are given a rating of 1. A Pairwise Comparison Matrix (PCM) established by Nhamo et al. (2019) was used to construct numerical correlations between the indicators listed in Table 7. Nhamo et al. (2018) and Mabhaudhi et al. (2019) provide the computation methodology for the PCM (Nhamo et al., 2020a). The scaling in Table 8 was used to classify the performance of WEF nexus indicators in the two study areas. For detailed information on the iWEF model, including methodology, the reader is referred to Nhamo et al. (2020a) and references therein.

Table 8: WEF nexus indicators performance classification categories. (Nhamo et al., 2020a).

Indicator	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
WEF nexus composite index	0-0,09	0,1-0,2	0,3-0,6	0,7-1

3.2.3. Water-Energy-Food Nexus Modelling Framework

To model and simulate the interlinkages between the WEF nexus resources, a system dynamics approach was considered. In this regard, a conceptual model that links the three main subsystems of water, energy, and food was designed. The relationships between the variables within and across the subsystems are represented as causal diagrams (loops), denoting either positive or negative feedback. The WEF nexus modelling framework considered in the current work integrated three main conceptual frameworks as follows;

a) The WEFSim model (see Wicaksono et al. 2019): a simulation model that implements a feedback analysis based on the supply and demand including availability and reliability of water, energy, and food resources; scalable in time and space and thus incorporates various scenarios configurations The key variables are the user reliability index for all resources as well as the total reliability index.
b) The WEF model is based on RBRs (see Wen et al. 2022): a feedback model for the WEF nexus from resources based on the regions while incorporating different future scenarios. This model has additional subsystems, including the environment, the economy, and society. The key variables are the water, energy, and food security indices.
c) An integrative analytical model for the WEF (see Nhamo et al., 2020a): A model that uses the AHP to establish quantitative relationships among the WEF sectors. The model's intricate interlinkages are simplified using a set of defined WEF nexus sustainability indicators. The key variables are the sustainability indicators and associated pillars for each resource.

The WEF nexus model formulations highlighted in (a) to (c) all consider the characteristics or elements of each subsystem whose linkages are represented by causal loop diagrams. For the current model development, the model described in Wen et al. (2022) is considered, and the following summarises the subsystems;

1) Water subsystem

- The supply side: surface water, groundwater, and recycled water constrained by rainfall
- The demand side: agriculture, industry, households, ecosystems
- Energy links: water demand for energy production and processing
- Food links: water demand for grain production and processing
- Society links: water demand for urban and rural households
- Overall demand side: collecting, treating, and distributing

2) Energy subsystem

- Supply-side: electricity (import), coal, renewable energy
- Demand-side: primary, secondary, and tertiary industries, and households
- Water links: energy demand for water extraction, treatment, and distribution
- Food links: energy demand for grain production
- Society links: energy demand for urban and rural households
- Economy links: energy demand for primary, secondary, and tertiary industries
- Overall demand for energy: generation and transporting

3) Food subsystem

- Supply-side: production of crop and meat-based products
- Demand-side: animal feed, industry, grain ration, grain loss, and sowing
- Energy links: crop demand for the production of biofuels,
- Society links: food demand for grain rations of urban and rural households
- Overall food demand: planting, transporting, and processing

4) Society subsystem

- Water, Energy, and Food security indices are limiting factors of population change, see Equation (1)

$$dP = \left(SI_{WEF} \times cr_p \times P\right)dt \qquad (1)$$

- In Equation (1), SI_{WEF}, SI_W, SI_E, and SI_F denote the combined WEF security indices while cr_p rate of change of the population.

5) Economy subsystem

- Water and Energy indices are the limiting factors of economic growth, see, Equation (2)

$$dQ_i = (SI_{WE} \times gr_i \times Q_i)dt \qquad (2)$$

- In Equation (2), SI_{WE}, and Q_i denotes the combined Water and Energy Security Indices, the output value for i^{th} (primary, secondary or tertiary) industry while gr_i is the growth rate for Q_i.

6) Environment subsystem

- Key considerations are the pollutant equivalents of water, environment, and CO_2 emissions using Equation (3).

$$E_p = \sum_{i=1}^{n} \frac{C_i}{W_i} \quad (3)$$

- In Equation (3), E_p is the pollutant equivalent, C_i is the emission (in kg) of the i^{th} pollutant, W_i is the i^{th} pollutant equivalent value (in kg) and n is the number of pollutants.

3.3. Results

3.3.1. Integrated Sectoral Interlinkages Based on WEF Nexus Modelling

Table 9 depicts the WEF nexus-based pairwise comparison matrix for Vhembe District Municipality. The pairwise comparison matrix was formulated using the climate-based knowledge of the municipality. The diagonal indicators assigned the value of 1,00 to represent values of unity. Only the upper half of the matrix was populated, and the lower triangle is the reciprocals. The highest considered value for the Vhembe District Municipality is 2, and it corresponds to water productivity-energy accessibility, water productivity-energy productivity, energy productivity-crop productivity, and food self-sufficiency-crop productivity paired with WEF nexus indices.

Table 10 presents the pairwise comparison matrix for the WEF nexus in Narok County, Kenya. Similar to the Vhembe case, climate-based knowledge of Narok County was used to formulate the resulting pair comparison matrix. The upper matrix scale for Narok County ranges from 1, where the paired WEF nexus indicators have equal contributions towards the WEF nexus objective, to 7,00, whereby the first indicator is strongly favoured over the second. Consequently, the scale of the reciprocated output shown at the lower triangle ranges from 1/7, indicating that the paired indicators are much less important, to 1,00, where the paired indicators contribute equally towards achieving the WEF nexus objectives in Narok County.

Table 9: Pair comparison matrix for WEF nexus in Vhembe District Municipality, South Africa.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1,00	1/3	1,00	1/5	1/5	1,00
Water productivity	3,00	1,00	2,00	2,00	1,00	1,00
Energy accessibility	1,00	1/2	1,00	1,00	1/3	1/5
Energy productivity	5,00	1/2	1,00	1,00	1,00	2,00
Food self-sufficiency	5,00	1,00	3,00	1,00	1,00	2,00
Crop productivity	1,00	1,00	5,00	1,00	1/2	1,00

Table 10: Pair comparison matrix for WEF nexus in Narok County, Kenya.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1,00	1,00	5,00	3,00	5,00	3,00
Water productivity	1,00	1,00	1,00	7,00	7,00	3,00
Energy accessibility	1/5	1,00	1,00	1,00	3,00	3,00
Energy productivity	1/3	1/7	1,00	1,00	1,00	2,00
Food self-sufficiency	1/5	1/7	1/3	1,00	1,00	2,00
Crop productivity	1/3	1/3	1/3	1/2	1/2	1,00

3.3.2. Normalized Pairwise Comparison Matrix for WEF Nexus Indicators

Results for the normalized pairwise matrix for the Vhembe District Municipality and Narok County are presented in Table 11 and Table 12, respectively. The normalized values for Vhembe range from the lowest of 0,032 for both water availability-energy productivity and water productivity-energy productivity, to the highest of 0,385 for Crop productivity-energy productivity paired indices. Similarly, the normalized pairwise comparison values for Narok County range from 0,038 for crop productivity-food self-sufficiency to the maximum of 0,577 for water availability-energy accessibility paired indices. For both sites, the corresponding Consistence Ration (CR) values, e.g. 0,096 (Vhembe) and 0,094 (Narok) are within the accepted range, as per the classification in Nhamo et al. (2020a). Furthermore, the composite integrated WEF nexus index, 0,191 for Vhembe is slightly higher as compared to the Narok County of 0,121.

Table 11: Normalized pairwise comparison matrix and composite indices for the Vhembe District Municipality.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity	Indices
Water availability	0,063	0,076	0,077	0,032	0,050	0,139	0,073
Water productivity	0,188	0,231	0,154	0,320	0,250	0,139	0,214
Energy accessibility	0,063	0,115	0,077	0,161	0,075	0,028	0,086
Energy productivity	0,312	0,115	0,077	0,161	0,250	0,278	0,198
Food self-sufficiency	0,312	0,231	0,231	0,161	0,250	0,278	0,243
Crop productivity	0,063	0,231	0,385	0,161	0,125	0,139	0,184
CR = 0,096							∑ = 1
Composite WEF nexus index (weighted average)							0,191

Table 12. Normalized pairwise comparison matrix and composite indices for Narok County.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity	Indices
Water availability	0,327	0,277	0,577	0,222	0,286	0,214	0,317
Water productivity	0,327	0,277	0,115	0,518	0,400	0,214	0,309
Energy accessibility	0,065	0,277	0,115	0,074	0,171	0,214	0,153
Energy productivity	0,108	0,039	0,115	0,074	0,057	0,143	0,089
Food self-sufficiency	0,065	0,039	0,038	0,074	0,057	0,143	0,069
Crop productivity	0,108	0,039	0,038	0,038	0,029	0,071	0,054
CR = 0,094							∑ = 1
Composite WEF nexus index (weighted average)							0,121

3.3.3. Performance of WEF Indicators in Vhembe District Municipality and Narok County

A spider or radar chart was used to assess the performance of the WEF nexus indicators across the two study sites. In each panel of Figure 23, the shaded-in spider chart plots the normalized data representing the performance of the six (6) selected WEF nexus indicators, in (a) Vhembe District Municipality and (b) Narok County. These indicators are displayed across multi-unique dimensions, ranging from 0,00 to 0,25 for Vhembe and 0,35 for Narok. According to Nhamo et al. (2020a), the degree of sustainable development of the indices increases with the scores from the central axis of the spider chart. Based on the results and the shape of the shaded-in spider graph, resource management relating to water, energy, and food supply vary across both sites. For instance, in the Vhembe district municipality, food security, which is represented by food self-sufficiency exhibits the highest score, followed by water productivity. Consequently, the focus in this district municipality is mainly on food security and water productivity compared to the other WEF nexus indicators. This implies that the degree of sustainable development of food security in Vhembe is higher. Furthermore, the degree of sustainable development of water availability significantly reduces (i.e. unsustainable development) within the study site.

In contrast to the Vhembe district municipality, the degree of sustainable development of water availability and water productivity is high in Narok County. The scores of the two WEF nexus indicators are very close, this is expected given that they are both clusters of the same resource (water resource). In addition, energy production, food security (e.g. food self-sufficiency), and cereal production exhibit almost similar points at the lowest scale. Consequently, the sustainability development of three indicators in Narok is a challenge. The integrated composite WEF nexus indices (weighted averages) for Vhembe District Municipality and Narok County are 0,197 and 0,216, respectively. The integrated composite indices classify both sites into the marginally sustainable category.

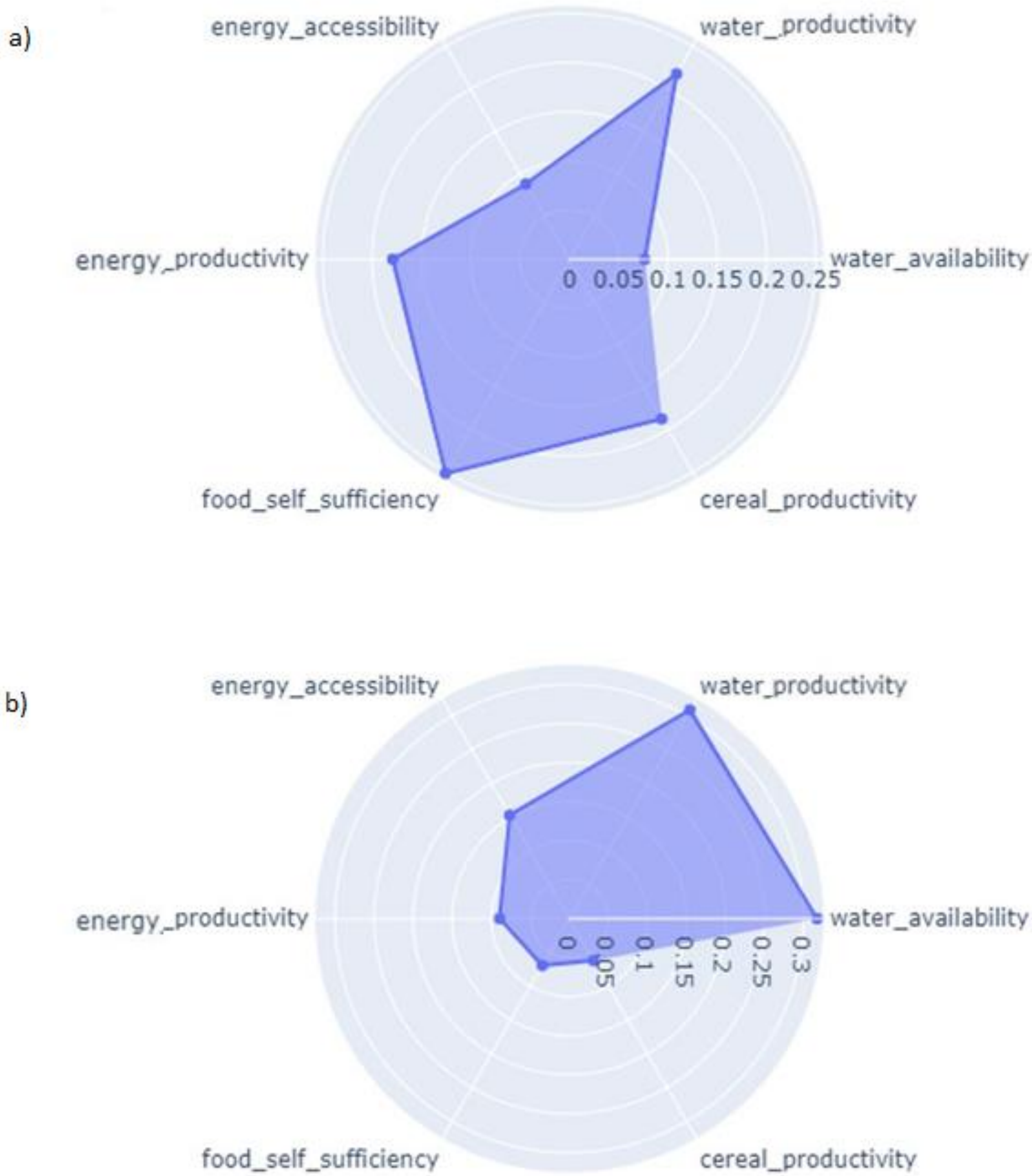

Figure 23: Resource performance in (a) the Vhembe District Municipality, South Africa and (b) Narok County, Kenya.

3.3.4. Integrated Sectoral Interlinkages Based on Survey Analysis

The pair comparison matrix shown in Table 13 was formulated based on different perceptions of WEF sectors collected from industry experts in the Vhembe District Municipality. Similar to the results from the model covered in section 3.1, the survey results follow a more or less similar pattern. The maximum value derived from the district municipality data is 1,86, which corresponds to water productivity-energy accessibility paired indicators. The 1,25 value corresponding to crop productivity-energy productivity was the second-highest numerical value obtained, with food self-sufficiency-energy accessibility, represented by the third highest-ranking value of 1,11. Table 14 shows Vhembe 's normalized pairwise matrix values range from 0,141 to 0,181 for water availability-crop productivity and water availability-energy accessibility paired indices. The CR value for Vhembe is 0,06, which is within the acceptable range according to Nhamo et al (2020a) categorization.

Table 13. Pairwise comparison matric of WEF nexus indicators for Vhembe District Municipality, based on the survey.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity
Water availability	1,00	1,08	1,03	1,03	0,89	0,89
Water productivity	0,94	1,00	1,86	0,88	0,86	0,93
Energy accessibility	0,96	1,16	1,00	1,08	1,11	1,11
Energy productivity	0,96	1,14	0,93	1,00	1,08	1,25
Food self-sufficiency	1,12	1,16	0,90	0,94	1,00	1,16
Crop productivity	1,12	1,08	0,90	0,80	0,86	1,00

Table 14. Normalized pairwise comparison matrix and composite indices for Vhembe based on survey analysis.

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity	Indices
Water availability	0,164	0,163	0,184	0,181	0,154	0,141	0,164
Water productivity	0,152	0,151	0,153	0,154	0,148	0,146	0,151
Energy accessibility	0,158	0,175	0,178	0,188	0,192	0,176	0,178
Energy productivity	0,158	0,172	0,165	0,175	0,186	0,196	0,175

	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity	Indices
Food self-sufficiency	0,183	0,176	0,160	0,162	0,172	0,183	0,172
Crop productivity	0,183	0,162	0,160	0,140	0,149	1,158	0,159
CR = 0,06							∑ = 1
Composite WEF nexus index (weighted average)							0,169

3.4. Discussion

Understanding the interlinkages between water, energy, food and resources forms the basis for better management and planning of these three key economic sectors. In addition, practical strategies to optimize WEF resources and promote sustainable management are urgently needed to minimize socioeconomic trade-offs and environmental threats (Hoff, 2011). Such interventions (aimed at ensuring equitable access and efficiency in WEF resource use) should be tailored to fit local context and capabilities to foster and sustain the wellbeing of vulnerable communities and livelihood outcomes in support of SDGs (Hoff, 2011). To contribute to this effort, this work assessed WEF nexus resources in Vhembe District Municipality, South Africa and Narok County, Kenya. Based on the results, it is evident that there is a resource management imbalance in both the Limpopo District Municipality and Narok County. This calls for the formulation of appropriate policies and strategies that will enact and strengthen interlinkages of the WEF elements at the community level.

3.4.1. Implications in terms of sustainability of resources

The main focus in the Vhembe District Municipality is on food self-sufficiency and water productivity compared to the other indicators. These results are in agreement with a case study for South Africa (Nhamo et al., 2020a), which also indicated an evident focus on food security and water productivity at the expense of other sectors. On the contrary, water availability and energy accessibility are the worst-performing indicators as shown in Table 7 and Figure 6a. Generally, South Africa is a water-scarce country and the higher water productivity index for the municipality could be due to limited water resources and access to water services, resulting in higher water use efficiency (Nesamvuni, 2022). This is supported by the Vhembe District Municipality 2019/20 IDP Review, which specifies that the 25 litres/capita/day for the district is not regarded as being a sustainable sufficient supply. The district is aiming to improve access to water services through the provision, operation and maintenance of socioeconomic water infrastructure. Energy accessibility is also very low (0,086) for the district, although energy productivity is relatively high (0,198). According to Rasimphi and Tinarwo (2020), more than 60% of households rely on fuelwood as the main energy source for cooking, heating, and other uses. Water availability and energy accessibility challenges in the district will increase due to limited water resources and climate change impacts. The municipality is classified into a marginally sustainable category with an integrated composite index value of 0,191, as shown in Table 7. Therefore, water resource management and clean energy production as well as access need to be improved for the district municipality to ensure water, energy, and food security and sustainable resource utilization and management.

The main focus in Narok County is on water availability and water productivity compared to the other indicators. Higher water availability and productivity indicator values presented in Table 8 suggest the need for efficient water use in the County. However, there are evident imbalances in the WEF nexus resource indicators showing very low performances from the crop productivity, food self-sufficiency, and energy productivity indicators. The quality and quantity of water in Narok County have declined due to rapid population growth and land use and land cover changes which directly impact water resources and agricultural production (KWTA, 2015). In addition, there is a lack of basic agricultural inputs, modernised technology, and adequate financial and extension services to promote sustainable production in Narok County (Lawrence and Rotich, 2021). The impact of climate change on the WEF sectors such as droughts and floods is also becoming more frequent, more severe, and less predictable in the County (Korir and Ngenoh, 2019). Energy production is mainly from hydro-power plants which rely on water resources and from firewood collected by clearing forests which are extremely critical for soil and water conservation in the catchments (KWTA, 2015). An integrated composite index of 0,121 classifies Narok County into a marginally sustainable category. For sustainable resource management in the County, all sector indicators should increase to the highest index which is 0,32, and attain a circular shape of the spider graph as shown in Figure 6b. Population increase and climate change impacts on the WEF sectors are the major factors affecting water resource utilization and management in Narok County (Rutto, 2014). Therefore, water resources management needs to be improved by increasing efforts to save the catchment areas from human exploitation to achieve sustainable WEF resources utilizations.

3.4.2. Implications in Terms of Policy and Developmental Options

The assessment of interactions and trade-offs of the WEF nexus indicators in the study sites shows that there is a need for integrated planning and utilisation of resources. The outcomes also enable stakeholders to easily understand and conceptualise the complex interlinkages among the WEF resources. The main focus on only a few indicators, food security and water productivity (Vhembe), and water availability and water productivity (Narok) is a clear indication that resources are not well managed sustainably within the two regions. Based on these outcomes, it is recommended that both study sites consider more efficient and integrated ways of allocating resources to improve other indicators without compromising food security, and water availability productivity. The outcomes of the assessments can help inform policy interventions related to the assessment and test the performances of the indicators concerning relevant policies for both Kenya and South Africa. Furthermore, the use of this and other similar tools have the potential of changing the way policies are framed by focussing on the integrated approach as opposed to the silo approach (i.e. energy or food or water only approach) to policy development. Additionally, it is recommended that similar assessments of cross-sectoral interactions among resources be conducted in other regions to obtain the necessary information that can be used as inputs in the development of policies and also informs on WEF nexus areas that need to be balanced in various regions. This work further strengthens the outcomes of research work reported by Botai et al. (2021) which investigated case studies and provided guidelines for WEF nexus implementation in Africa. Furthermore, the results of this work can be used as evidence in support of the recommendations reported in Aboelnga et al. (2018a) that there is a need to support integrated transboundary management of the basin and to design policies to holistically attain these development objectives by seeking efficiency of resource us to address pressing developmental challenges that include food insecurity, poverty, unreliable rain, and highly variable inter-and intra-annual river flows. The performances of resource utilisation and management investigated in this study thus provide an understanding of WEF components interactions and trade-offs at local levels and can form the basis for policy development and align the policies with sustainable developmental goals.

3.5. Concluding Remarks

In this contribution report, the iWEF nexus analytical model was utilised to evaluate interlinkages among variables relating to water-energy-food resources in the Vhembe District Municipality, South Africa and Narok County in Kenya. Six (6) built-in WEF nexus indicators in the iWEF model were assessed based on two-step approaches, namely, desktop analytic study and questionnaire survey. The integrated composite indices for Vhembe and Narok suggest that resource management is marginally sustainable in both river basins. In addition, there is evidence of imbalanced resource management across the river basins. For instance, while the degree of sustainable development of food security and water productivity is higher in Vhembe, the main focus in Narok County is water availability and productivity. The findings of this study contribute towards decision-making in support of effective management of water-energy-food resources in the two study sites.

4. ASSESSMENT OF RURAL LIVELIHOODS, HEALTH AND WELLBEING USING THE WEF NEXUS MODEL

4.1. Introduction

Water, energy, and food are considered complex resources or sectors with inextricable interdependences (St, 2019, IUCN ROWA, 2019). This is because these three resources are interlinked in an influential manner, where the change in one, coupled with climate-related and social changes (see summary in Figure 24), can influence the other two resources (Nhamo et al., 2018), particularly in energy-intensive, water-scarce and food deficient regions (St, 2019; IUCN ROWA, 2019). Understanding the complex and dynamic relationship between water, energy and food as well as achieving effective sustainable resource management thereafter requires an integrated nexus approach. The nexus approach integrates and facilitates cross-cutting management and governance sectors, trade-offs, and synergies between the components, taking into account the different economic, social and environmental factors related to them (Leck et al., 2015).

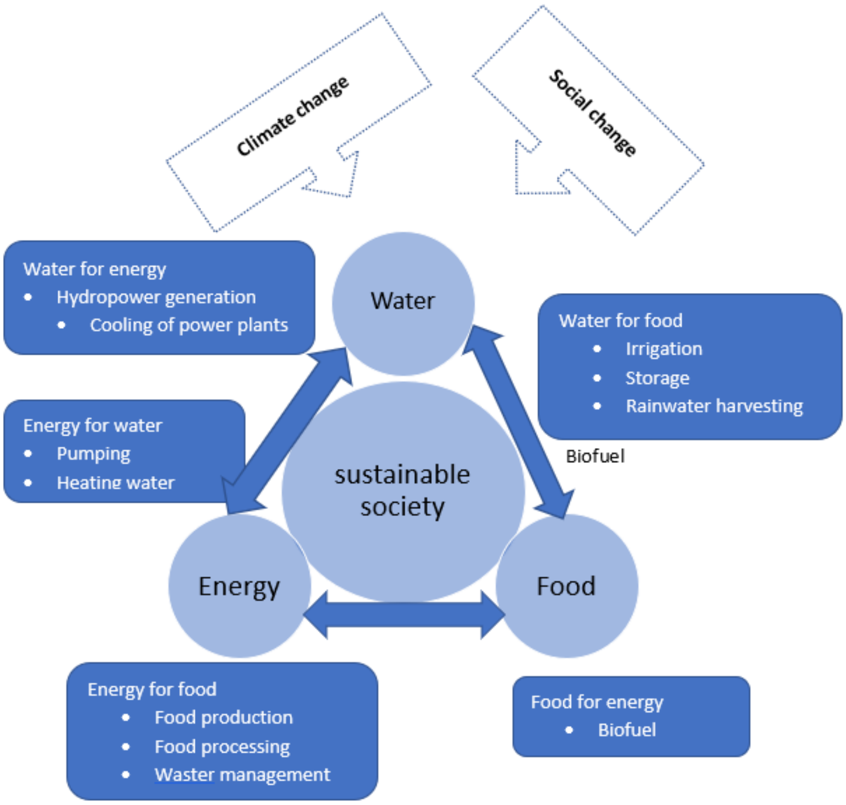

Figure 24. Multifaceted linkages between the Water-Energy-Food nexus.

The WEF nexus is now recognised as an integrated approach used in three-dimensional aspects, to study dynamic processes and interrelationships between water, energy and food security for effective resource planning and management, in a changing climate (Nhamo et al., 2020b). In this regard, the first dimension of the WEF nexus approach (e.g. an integrated analytical tool) addresses interlinkages amongst the WEF resources based on qualitative and quantitative methods; the second dimension (e.g. a conceptual framework) streamlines understanding of WEF interlinkages thereby promoting coherence in policy and decision-making processes, as well as highlighting the trade-offs and synergies between the three sectors; whereas the third dimension (a discourse) of the WEF nexus promotes governance cross-sectoral cooperation (Albrecht et al., 2018; Nhamo et al., 2020b). In addition, considering that the security of the three resources is regarded as essential for sustainable development, the WEF nexus approach can also be used to monitor the performance of the WEF nexus indicators linked to human-development Sustainable Development Goals (SDGs) (Stephan et al., 2018), which have been set to strengthen the economic, environmental, and social sectors of the world. As highlighted in Albrecht et al. (2018), the WEF nexus approach aid efforts toward (1) resource efficiency, (2) policy integration, (3) sustainability, (4) economic efficiency, (5) adaptation and resilience, (6) human and resource security and (7) environment and ecosystem.

While the SDGs span a wide spectrum of themes and issues, the main goals that are directly linked to the WEF nexus paradigm are:

- Food security (SDG 2) – the goal that seeks to end hunger by attaining food security, improving diet and supporting sustainable agriculture.
- Good health and wellbeing (SDG 3) – ensure healthy lives and promote well-being for all age groups,
- Sustainable water management (SDG 6) – ensure availability and sustainable management of water and sanitation for all,
- Affordable and clean energy (SDG 7) – ensure access to affordable, reliable, sustainable and modern energy for all
- Climate action (SDG 13) – take urgent action to combat climate change and its impacts.

The WEF nexus tool is therefore essential to evaluate and monitor the performance of these SDGs, as linked to the livelihoods, human health and well-being as well as the sustainable production of the WEF resources. Krantz (2001) describes livelihood as the ability to obtain basic needs such as food, water, energy, and clothing. Tools such as the sustainable livelihoods framework can thus be integrated into studies that seek to understand the WEF at the community or household level by assessing how people use their capabilities and assets (natural, physical, social, human, and financial) to sustain themselves and the shocks and stresses (risks) to livelihoods (Carney, 2003). The approach also highlights the different conceptions of well-being as well as the different levels of vulnerability (de Satge, 2000). Furthermore, it provides avenues that can be used to develop interventions to optimize current and identify new sustainable livelihood strategies that are resilient to shocks and stresses.

Various definitions of wellbeing have been reported in the literature, however, none are unanimously accepted (Brown and Westaway, 2011). Alkire and Foster (2011), and Loveridge et al. (2020) however argue that the concept of wellbeing entails multidimensional development, building on an understanding of what people need to participate and flourish in society. The scarcity of WEF resources, has direct and indirect impacts on human health, well-being, and livelihoods of people, particularly the rural communities making the WEF nexus central to discussions regarding the development and subsequent monitoring of the related SDGs. Nonetheless, the assessment of these goals is often hampered by challenges, particularly in rural areas where it is difficult to access food, electricity, fuel, and sanitation.

The United Nations is working towards setting new goals and targets for the post-2015 agenda aimed at achieving the long-term sustainable development of human society thus including sustainable water use, energy use, and agricultural practices, as well as promoting more inclusive economic development (United Nations, 2014). The organization recognises poverty eradication, changing unsustainable patterns of consumption and production, protecting and managing the natural resource base of economic and social development as the overarching objectives and essential requirements for sustainable development. Currently, socioeconomic factors such as population growth, economic development and changing patterns are causing unprecedented stress on the WEF resources. With the climate projected to increase in the near future, it is expected that the demand of the population to access the WEF resources and services will grow spontaneously. Consequently, assessing the availability of WEF resources in changing climate is essential for policy and decision-making to mitigate deficiencies in the three sectors. In this regard, the current study aims to assess the livelihoods, human health and wellbeing in the selected sites of the Limpopo and Mara River basins, in South Africa and Kenya, respectively, based on the WEF nexus method.

4.2. Material and Methods

4.2.1. Selection of Sustainable Livelihood, Health and Wellbeing Indicators

From a review of WEF literature, the study identified indicators which were refined and produced a small set (Table 15) that highlights the interactions between the nexus aspects and their impact on livelihoods, human health and wellbeing (Pahl-Wostl, 2019; Abubakar, 2021; Wolde et al., 2022). Indicators have been adopted in WEF nexus studies as they support monitoring and evaluation as well as sustainable use of nexus resources to achieve global and national development goals such as SDGs 2, 3, 6, 7 and 13.

Table 15: Sustainable livelihood, human health, and wellbeing metrics.

Drivers of livelihood changes	Subjective Indicators
Population growth and urbanisation	• Population growth rate • Rate of urbanisation and migration • Land use and land-use change • Land productivity • The proportion of water used per sector • Access to sanitation
Climate change	• Climate risks and associated impacts (Changes in weather and climate variables such as rainfall and temperature) • Exposure and sensitivity to risks • The proportion of rainfed agriculture
Poverty and unemployment	• Poverty levels • Unemployment levels • Accessibility and affordability of nutritive food • Malnutrition and mortality • Food insecurity
Weak Governance Systems	• Poor resource planning and management • Existing policies and other policy instruments • Supportive government institutions and structures • Wellbeing and governance • Access to Water-Energy-Food resources • Access to clean drinking water at the household level • Water quality

4.2.2. Data Collection and Method of Analysis

The study adopted mixed methods to collect data including focus group discussions, interviews and an online survey that was developed and circulated to households, government actors and business owners in the study sites. The survey data was complemented with information from interviews and focus group discussions that provided rich narratives. The participants highlighted some of the complex interlinkages between nexus components, what and how climate hazards had affected them, and how they currently cope including the role of indigenous knowledge in understanding changes in weather and climate and recommendations on what can be done to support climate change adaptation as well as water, energy and food security in the study sites.

The following algorithm outlines the procedure used to analyse and present the survey responses:

- A survey questionnaire was structured using a scale of 1-5; where 1 –Strongly Disagree; 2 – Disagree; 3 – Neither Agree nor Disagree; 4 – Agree and 5 – Strongly Agree, see questionnaire in Appendix 2.

- From the survey responses, the assessment of respondents' pairwise consistency was based on Saaty's scaling reported in, e.g. Nhamo et al. (2020)a; Wolde et al. (2022); Hernández-Alemán et al. (2022) and references therein.
- Only pairwise respondents whose Consistency Ratio (CR) of up to 10% was used to generate the pairwise comparison matrix reported in for example Mabhaudhi et al. (2019) and Nhamo et al. (2020a).
- The pairwise matrix was then normalized following the methodology reported by Nhamo et al. (2020), from which the CR and the weighted integrated index were derived
- The spider diagrams were generated to assess the performance of the sustainable indicators
- To establish the linkages between the sustainable livelihood indicators and the WEF resources, steps 4 and 5 were repeated for each indicator of the WEF components independently.

Lastly, a correlation analysis was performed to determine the significant association between the WEF nexus resources and sustainable livelihood indicators

4.3. Results

4.3.1. Pairwise Comparison Matrix for Sustainable Livelihood Indicators

This study provides the impact of climate change using specific climate sustainable indicators related to the water, energy, and agriculture sectors. Given in Table 16 and Table 17 are the pairwise comparison matrix formulated using selected climate sustainable indicators based on local knowledge gathered during stakeholders' engagement/questionnaire administration, in Narok County and Vhembe District Municipality, respectively. The climate sustainable indicators included 1) population & urbanisation – En1; 2) Climate Change – En2; 3) Risks-vulnerability – R1x; 4) Exposure-sensitivity – R2x; 5) wellbeing & governance – I; 6) Health-water quality – H1; and 7) Health-Malnutrition – H2. Following Nhamo et al. (2020), the diagonal indicators are assigned the value of 1,00 to represent values of unity. Only the upper half of the matrix was populated, and the lower triangle is the reciprocals. The values of the paired matrix range from the lowest 0,82 to the highest of 1,22 for Narok County and from 0,35 to 2,88 for Vhembe District Municipality.

Table 16. Pairwise comparison matrix of sustainable livelihood, health and wellbeing indicators for Narok County. Definition of abbreviations: En1 – population & urbanisation; En2 – Climate Change; R1x – Risks-vulnerability; R2x – Exposure-sensitivity; I – wellbeing & governance; H1 – Health-water quality; H2 – Health-Malnutrition.

	En1	En2	R1x	R2x	I	H1	H2
En1	1,00	1,05	1,05	1,00	0,96	0,93	0,93
En2	0,95	1,00	0,93	0,90	0,88	0,95	0,86
R1x	0,95	1,07	1,00	0,82	0,82	0,90	0,94
R2x	1,00	1,11	1,22	1,00	0,86	0,82	0,82
I	1,04	1,14	1,22	1,16	1,00	0,89	0,93
H1	1,08	1,06	1,12	1,22	1,13	1,00	1,00
H2	1,08	1,16	1,06	1,22	1,08	1,00	1,00

Table 17. Same as Table 16 but for Vhembe District Municipality.

	En1	En2	R1x	R2x	I	H1	H2
En1	1,00	1,44	1,00	0,69	1,00	0,69	1,00
En2	0,69	1,00	0,48	0,41	0,48	0,48	0,44
R1x	1,00	2,08	1,00	0,35	0,44	0,44	0,83
R2x	1,44	2,47	2,88	1,00	0,83	0,58	0,83
I	1,00	2,08	2,26	1,20	1,00	0,83	1,57
H1	1,44	2,08	2,26	1,73	1,20	1,00	1,89
H2	1,00	2,26	1,20	1,20	0,64	0,53	1,00

The results for the normalized values of sustainable livelihoods, human health and wellbeing indicators for Narok County are presented in Table 18. The values range from the lowest value of 0,112 for Risks-vulnerability (R1x) and Exposure-sensitivity (R2x) to the highest value of 0,168 for wellbeing & governance (I) and Health-water quality (HI). The second highest score is 0.166 observed between Exposure-sensitivity (R2x) and Health-water quality (HI) as well as Exposure-sensitivity (R2x) and Health-Malnutrition (H2). The result shows a corresponding Consistency Ratio (CR) value of 0,046 (or 4,6%) and a composite integrated WEF nexus index of 0,143. Similarly, to Narok County, the highest value for Vhembe District Municipality is 0,260, which corresponds to the Exposure-sensitivity (R2x) and Health-water quality (HI) paired sustainable indicators, followed by Exposure-sensitivity (R2x) and Risks-vulnerability (R1x) paired indicators at 0,256. Risks-vulnerability (R1x) and Climate Change (En2) and Exposure-sensitivity (R2x) and Risks-vulnerability (R1x) have the lowest values of 0,04 and 0,05, respectively (see results in Table 19). Vhembe District municipality has a CR value of 0,067, which is 0,021 higher than Narok County. The results suggest that water resources in Vhembe District are more sustainable than those in Narok County. The CR values for both study sites are within the accepted range according to the classification in Nhamo et al. (2020a).

Table 18. Normalized pairwise comparison matrix of sustainable indicators and composite index for Narok County.

	En1	En2	R1x	R2x	I	H1	H2	index
En1	0,141	0,138	0,138	0,137	0,143	0,143	0,143	0,141
En2	0,134	0,132	0,123	0,123	0,131	0,146	0,133	0,132
R1x	0,134	0,141	0,132	0,112	0,122	0,138	0,145	0,132
R2x	0,141	0,146	0,160	0,137	0,128	0,127	0,127	0,138
I	0,146	0,150	0,160	0,158	0,148	0,137	0,143	0,149
H1	0,152	0,139	0,147	0,166	0,168	0,154	0,154	0,154
H2	0,152	0,153	0,140	0,166	0,160	0,154	0,154	0,154
CR = 0,046								∑ = 1
Composite integrated index (weighted average)								0,143

Table 19. Same as Table 18 but for Vhembe District Municipality.

	En1	En2	R1x	R2x	I	H1	H2	index
En1	0,132	0,108	0,090	0,105	0,179	0,152	0,132	0,128
En2	0,091	0,075	0,043	0,062	0,086	0,106	0,058	0,074
R1x	0,132	0,155	0,090	0,053	0,079	0,097	0,110	0,102
R2x	0,190	0,184	0,259	0,152	0,149	0,127	0,110	0,167
I	0,132	0,155	0,204	0,183	0,179	0,183	0,208	0,178
H1	0,190	0,155	0,204	0,263	0,215	0,219	0,249	0,214
H2	0,132	0,169	0,108	0,183	0,114	0,116	0,132	0,136
CR = 0,067								∑ = 1
Composite integrated index (weighted average)								0,143

The spider graphs are used to calculate the different significance of resource indicators and their ranking. In this regard, low weights indicate less significance whereas higher weights reflect higher importance. The spider or radar chart for sustainable livelihoods, human health and wellbeing indicators in Narok County is shown in Figure 25. The figure indicates that wellbeing & governance and Health-water quality; Exposure-sensitivity and Health-Malnutrition are the most related having a score of 0,23. Other closely related indices include Risks-vulnerability, well-being and governance.

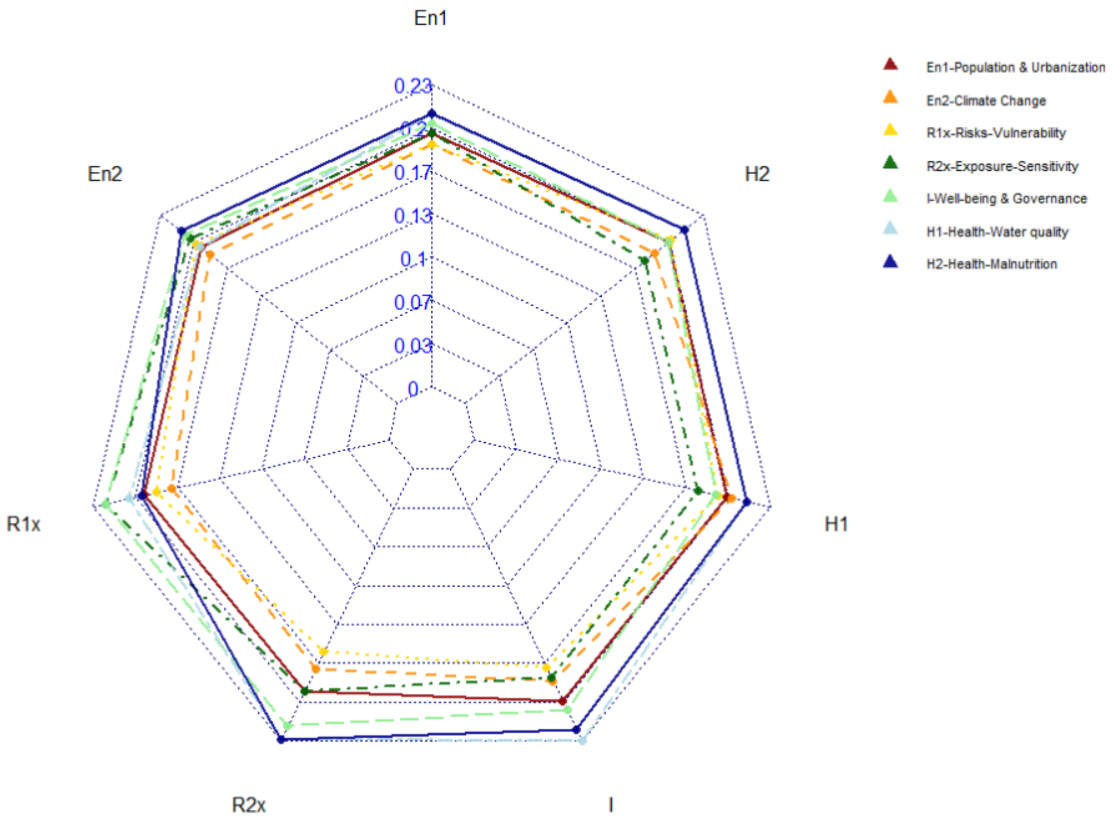

Figure 25. Performance of sustainable livelihoods, human health and wellbeing indicators – Narok County.

Figure 26 depicts the performance of indicators for sustainable livelihoods, human health, and well-being in Vhembe District Municipality, as represented by a spider graph. The range of weighting values is between 0,05 and 0,32. In comparison to other sustainable livelihood indicators, the results show that exposure-sensitivity (R2x) and risk-vulnerability (R1x) have the greatest impact. Following these is the health-malnutrition (H2) indicator. Based on the results, the Climate change (En2) indicator, has less impact on the sustainable livelihood in Vhembe District Municipality, with Health-Water quality (H1) and Well-being & Governance having a fair impact.

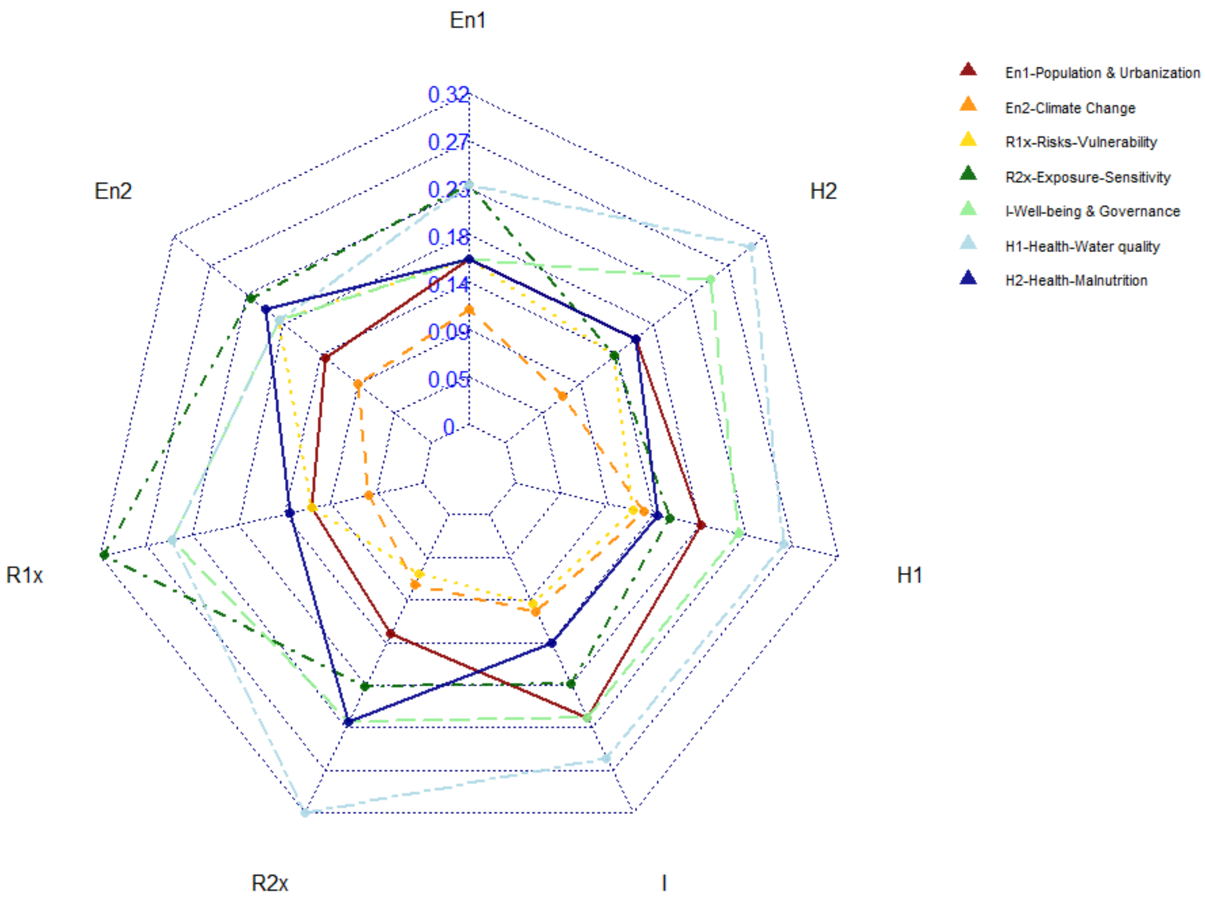

Figure 26. Performance of sustainable livelihoods, human health and wellbeing indicators – Vhembe District Municipality.

4.3.2. Impacts of WEF Resources on the Sustainability of Livelihood Indicators

4.3.2.1 Water and Sustainable Livelihood Indicators

According to the results that are presented in Table 20, the pairwise matrix values are high, with a value of 1.55, for both the well-being and governance (I)/population & urbanisation (En1) as well as the well-being and governance (I)/climate change (En2) paired sustainable livelihoods indicators. The lowest paired matrices correspond to H2/R1x (risks-vulnerability/health-malnutrition) and W2/R1x (water productivity/risks-vulnerability), given by the value of 0,64. Participants in Narok indicated that many rivers in the county had been affected by population growth and the clearing of forests due to the increased number of people moving to urban areas. The Ogiek community in the Mau Forest was among the most affected communities as they are nomads who now have to travel long distances to get water for their livestock. The men usually leave women and children to fend for themselves however, the well-being of these families was more vulnerable as other livelihood activities such as beekeeping had also been affected by deforestation. In Table 21, The pairwise comparison matrix of water indicators for the Vhembe District Municipality is shown. The values are all one, indicating that all of Vhembe's sustainable indicators are equally important, with an index of (1/1) observed across all pairs.

Table 20. Pairwise comparison matrix of sustainable indicators and water indicators for Narok County. W1 – Water access and W2 – Water productivity.

	En1	En2	R1x	R2x	I	H1	H2	W1	W2
En1	1,00	1,25	1,25	1,00	1,55	1,25	1,25	1,25	1,00
En2	0,80	1,00	1,00	0,80	1,55	1,25	1,25	1,00	1,25
R1x	0,80	1,00	1,00	1,00	0,80	0,80	0,64	0,80	0,64
R2x	1,00	1,25	1,00	1,00	1,55	1,25	1,25	1,00	1,25
I	0,64	0,64	1,25	0,64	1,00	1,00	1,38	1,25	1,00
H1	0,80	0,80	1,25	0,80	1,00	1,00	1,00	0,80	1,00
H2	0,80	0,80	1,55	0,80	0,72	1,00	1,00	0,80	1,25
W1	0,80	1,00	1,25	1,00	0,80	1,25	1,25	1,00	0,80
W2	1,00	0,80	1,55	0,80	1,00	1,00	0,80	1,25	1,00

Table 21. Pairwise comparison matrix of sustainable indicators and water indicators for VDM. W1 – Water access and W2 – Water productivity.

	En1	En2	R1x	R2x	I	H1	H2	W1	W2
En1	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
En2	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
R1x	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
R2x	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
I	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
H1	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
H2	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
W1	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
W2	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00

Table 22 shows the results for the normalized values of water indicators. The lowest value is 0,70 observed in three sub-indicator pairs that include Wellbeing & Governance (I)/ Health-Malnutrition (H2); Health-Malnutrition (H2)/ risks-vulnerability (R1x) and Water productivity (W2)/ Risks-vulnerability (R1x). The highest value is observed for the Wellbeing & Governance (I) and population & urbanisation (En1) as well as Wellbeing & Governance (I) and Climate Change (En2) pairs. The corresponding CR value is 0,053 (e.g. 5.3%), with a weighted average of 0,111.

Table 22. Normalized pairwise comparison matrix of sustainable indicators and water indicators as well as the composite indices for Narok County.

	En1	En2	R1x	R2x	I	H1	H2	W1	W2	index
En1	0,131	0,146	0,112	0,127	0,155	0,127	0,127	0,136	0,109	0,130
En2	0,105	0,117	0,090	0,102	0,155	0,127	0,127	0,109	0,136	0,119
R1x	0,105	0,117	0,090	0,127	0,080	0,082	0,066	0,088	0,070	0,092
R2x	0,131	0,146	0,090	0,127	0,155	0,127	0,127	0,109	0,136	0,128
I	0,084	0,075	0,112	0,082	0,100	0,102	0,141	0,136	0,109	0,105
H1	0,105	0,094	0,112	0,102	0,100	0,102	0,102	0,088	0,109	0,102
H2	0,105	0,094	0,140	0,102	0,073	0,102	0,102	0,088	0,136	0,105
W1	0,105	0,117	0,112	0,127	0,080	0,127	0,127	0,109	0,087	0,110
W2	0,131	0,094	0,140	0,102	0,100	0,102	0,082	0,136	0,109	0,111
CR = 0,053										∑ = 1
Composite integrated index (weighted average)										0,111

The impacts of water resources on sustainable livelihood indicators are assessed based on a spider diagram shown in Figure 27. The selected metrics for the water component of the WEF resources are water access (W1 in royal blue) and water productivity (W2 in purple). The impacts of these water indicators are assessed based on their position within the spider graph concerning the sustainable livelihoods, human health and wellbeing indicators. As given in Figure 27, the weighting values for water productivity range from a low weighting value of 0,13 for health-malnutrition (H2) to a high weighting value of 0,20 for water access (W1). In general, the results indicate that the impact of water productivity on sustainable livelihoods in Narok County is mostly high for the following indicators: population growth and urbanisation, water access, and vulnerability and risks. In terms of water access, the impacts are high on health-water quality, health-malnutrition, as well as on population and urbanisation, and exposure sensitivity. The general performance of water and sustainability livelihood indicators suggests that there is a need to improve water access to match population growth and urbanisation in Narok County as key institutions such as schools have water challenges (see Figure 28). Governance actors need to be more proactive in enforcing water by-laws and reducing pollution of rivers in the county as well as the country in general.

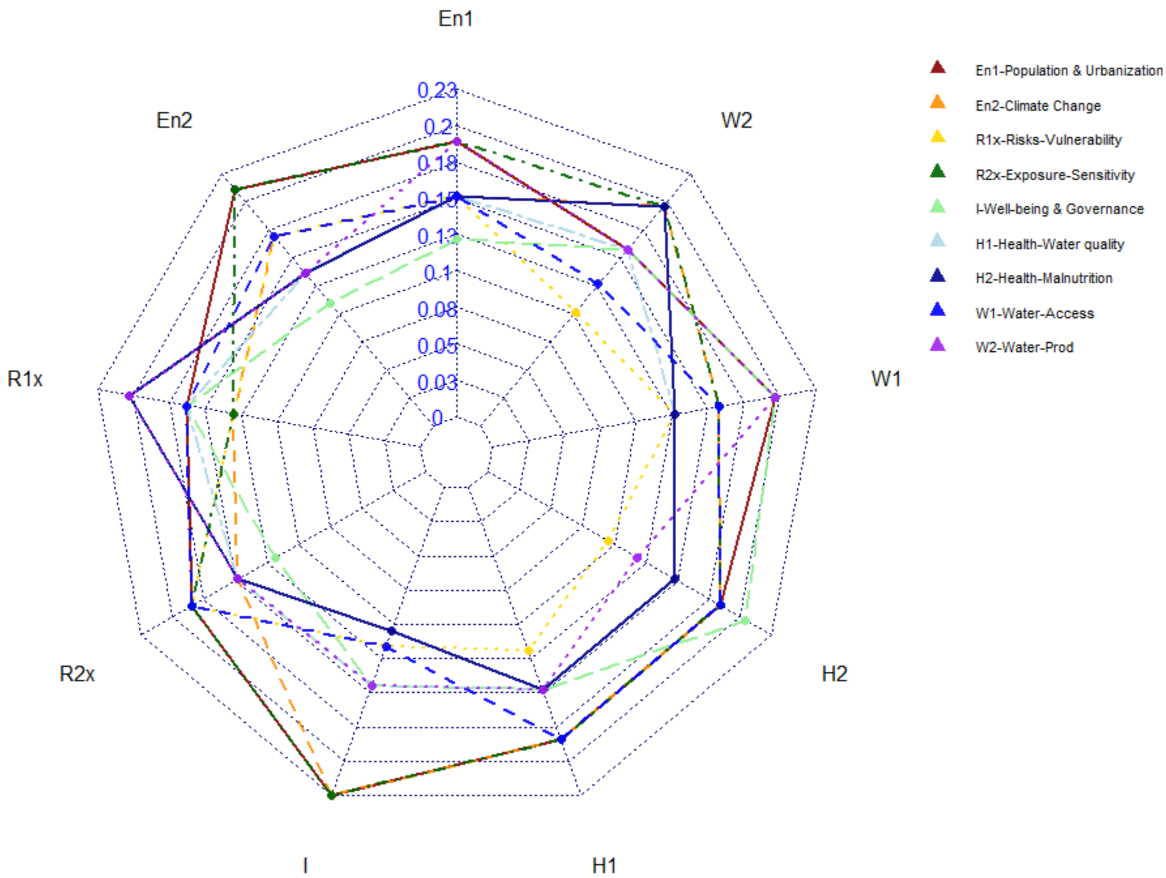

Figure 27. Performance of sustainable livelihood indicators against water indicators – Narok County.

Figure 28. Schoolchildren travel long distances to fetch water to use at school.

4.3.2.2. Energy and Sustainable livelihood Indicators

The paired matrix includes accessibility and productivity drivers of change for energy resources, a component of the WEF nexus resources. Based on the results presented in Table 23, pairwise matrix values range between 0,64 and 1,93. The highest value of 1,93 corresponds to H2/R1x (health-malnutrition/risks-vulnerability) and R1x/H2 (risks-vulnerability/health-malnutrition) paired sustainable indicators. The pairwise matrix between most sustainable livelihood, health and wellbeing and energy indicators depicts close to unity values, suggesting that the paired indicators are almost equally important in Narok County.

Table 23. Pairwise comparison matrix of sustainable indicators and water indicators for Narok County, where E1 – energy access and E2 – energy productivity.

	En1	En2	R1x	R2x	I	H1	H2	E1	E2
En1	1,00	1,25	1,25	1,00	1,55	1,25	1,25	1,25	1,00
En2	0,80	1,00	1,00	0,80	1,25	1,00	1,00	0,80	1,00
R1x	0,80	1,00	1,00	0,80	0,64	0,64	0,52	0,64	0,64
R2x	1,00	1,25	1,25	1,00	1,25	1,00	1,00	0,80	1,00
I	0,64	0,80	1,55	0,80	1,00	1,00	1,55	1,25	1,00
H1	0,80	1,00	1,55	1,00	1,00	1,00	1,00	0,80	1,00
H2	0,80	1,00	1,93	1,00	0,64	1,00	1,00	1,00	1,55
E1	0,80	1,25	1,55	1,25	0,80	1,25	1,00	1,00	1,00
E2	1,00	1,00	1,55	1,00	1,00	1,00	0,64	1,00	1,00

For the Vhembe District Municipality, the results that are presented in Table 24, show the pairwise matrix range between 0,58 and 1,73. The highest value of 1,73 corresponds to the following paired sustainable indicators: well-being and governance (I), to climate change (En2), risks-vulnerability (R1x), exposure-sensitivity (R2x); health-water quality (H1) to climate change (En2), risks-vulnerability (R1x), exposure-sensitivity (R2x); Health-Malnutrition (H2) to climate change (En2), risks-vulnerability (R1x), exposure-sensitivity (R2x), health-water quality (H1); energy-access (E1) to climate change (En2), risks-vulnerability (R1x), exposure-sensitivity (R2x), well-being and governance (I) and health-water quality (H1); energy productivity (E2) to climate change (En2), exposure-sensitivity (R2x), well-being and governance (I) and health-water quality (H1). The lowest value of 0,58 corresponds to the following paired sustainable indicators: climate change (En2) to well-being and governance (I), health-water quality (H1), Health-Malnutrition (H2), energy-access (E1) and energy productivity (E2); risks-vulnerability (R1x) to exposure-sensitivity (R2x), well-being and governance (I), health-water quality (H1), Health-Malnutrition (H2), and energy-access (E1); exposure-sensitivity (R2x) to well-being and governance (I), health-water quality (H1), Health-Malnutrition (H2), energy-access (E1), and energy productivity (E2); well-being and governance (I) to energy-access (E1) and energy productivity (E2); and health-water quality (H1) to Health-Malnutrition (H2), energy-access (E1), and energy productivity (E2).

The results reflect that the pairwise matrix among sustainable livelihood, health and well-being and energy indicators are close to unity values, suggesting that the paired indicators are almost equally important in the Vhembe District Municipality. The respondents in the Vhembe District Municipality indicated energy access and productivity are impacted by population and urbanisation, climate change and demand from various sectors as the economy grows.

Table 24. Pairwise comparison matrix of sustainable indicators and water indicators for VDM, where E1 – energy access and E2 – energy productivity.

	En1	En2	R1x	R2x	I	H1	H2	E1	E2
En1	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
En2	1,00	1,00	1,00	1,00	0,58	0,58	0,58	0,58	0,58
R1x	1,00	1,00	1,00	0,58	0,58	0,58	0,58	0,58	1,00
R2x	1,00	1,00	1,73	1,00	0,58	0,58	0,58	0,58	0,58
I	1,00	1,73	1,73	1,73	1,00	1,00	1,00	0,58	0,58
H1	1,00	1,73	1,73	1,73	1,00	1,00	0,58	0,58	0,58
H2	1,00	1,73	1,73	1,73	1,00	1,73	1,00	1,00	1,00
E1	1,00	1,73	1,73	1,73	1,73	1,73	1,00	1,00	1,00
E2	1,00	1,73	1,00	1,73	1,73	1,73	1,00	1,00	1,00

Similarly, table 25 depicts results for the normalized pairwise matrix for Narok County for the energy indicators. In this case, the normalized values range from the lowest of 0,070 for R1x/E2 (risks – vulnerability/energy productivity) to 0,146 for En1/E1 (population and urbanisation/energy access) paired with sustainability indicators for livelihood, human health and wellbeing. The corresponding CR value is 0,056 (5,6%) and is within the accepted range, as per the classification in Nhamo et al. (2020), while the composite integrated index (weighted average) across sustainable and energy indicators is 0,111. For the Vhembe District Municipality, the results for the normalized pairwise matrix for the energy indicators are shown in Table 26. The normalized values range from between 0,047 for risks – vulnerability/exposure-sensitivity (R1x/Rx2) and 0,188 for En1/E1 energy access/ well-being and governance (E1/I) and energy productivity/well-being and governance (E2/I) paired with sustainability indicators for livelihood, human health and wellbeing. The corresponding CR value is 0,038 (3,8%) and is within the accepted range, as per the classification in Nhamo et al. (2020), while the composite integrated index (weighted average) across the sustainable and energy indicators is 0,111.

Table 25. Normalized pairwise comparison matrix of sustainable indicators and energy indicators as well as the composite indices for Narok County, where E1 – energy access and E2 – energy productivity.

	En1	En2	R1x	R2x	I	H1	H2	E1	E2	index
En1	0,131	0,131	0,099	0,116	0,170	0,136	0,139	0,146	0,109	0,131
En2	0,105	0,105	0,079	0,093	0,136	0,109	0,112	0,094	0,109	0,105
R1x	0,105	0,105	0,079	0,093	0,071	0,071	0,058	0,075	0,070	0,081
R2x	0,131	0,131	0,099	0,116	0,136	0,109	0,112	0,094	0,109	0,115
I	0,084	0,084	0,123	0,093	0,109	0,109	0,173	0,146	0,109	0,115
H1	0,105	0,105	0,123	0,116	0,109	0,109	0,112	0,094	0,109	0,109
H2	0,105	0,105	0,153	0,116	0,071	0,109	0,112	0,117	0,169	0,117
E1	0,105	0,131	0,123	0,144	0,088	0,136	0,112	0,117	0,109	0,118
E2	0,131	0,105	0,123	0,116	0,109	0,109	0,072	0,117	0,109	0,110
CR = 0,056										∑ = 1
Composite integrated index (weighted average)										0,111

Table 26. Normalized pairwise comparison matrix of sustainable indicators and energy indicators as well as the composite indices for VDM, where E1 – energy access and E2 – energy productivity.

	En1	En2	R1x	R2x	I	H1	H2	E1	E2	index
En1	0,111	0,079	0,079	0,082	0,109	0,101	0,137	0,145	0,137	0,109
En2	0,111	0,079	0,079	0,082	0,063	0,058	0,079	0,084	0,079	0,079
R1x	0,111	0,079	0,079	0,047	0,063	0,058	0,079	0,084	0,137	0,082
R2x	0,111	0,079	0,137	0,082	0,063	0,058	0,079	0,084	0,079	0,086
I	0,111	0,137	0,137	0,142	0,109	0,101	0,137	0,084	0,079	0,115
H1	0,111	0,137	0,137	0,142	0,109	0,101	0,079	0,084	0,079	0,109
H2	0,111	0,137	0,137	0,142	0,109	0,174	0,137	0,145	0,137	0,136
E1	0,111	0,137	0,137	0,142	0,188	0,174	0,137	0,145	0,137	0,145
E2	0,111	0,137	0,079	0,142	0,188	0,174	0,137	0,145	0,137	0,139
CR = 0,038										∑ = 1
Composite integrated index (weighted average)										0,111

The impacts of energy access (E1) and productivity (E2) on sustainable livelihoods, human health and wellbeing indicators represented by the royal blue and purple colours respectively are depicted in Figure 29. Based on the spider chart, the impacts of energy security are less on wellbeing and governance (I) and relatively higher for population and urbanisation (En1) and energy productivity (E2). This implies that there is a need for decisions or policymakers to focus on energy provision to improve the livelihoods of the community and meet the energy demand due to the increasing population and urbanisation trends. Currently, deforestation is one of the major environmental problems identified in Narok as communities cut down trees for firewood and charcoal and have contributed to increased soil erosion and degradation (See Figure 30). The Narok country has no energy policy to support the uptake of renewable energy or regulate the use of non-renewable energy sources such as charcoal, which is sold by several people, hence, a source of livelihood. A high impact is observed for risks and vulnerability (R2x) with a weighting value of 0,21, followed by climate change (En2) and health-water quality (H1). Energy productivity is high on population and urbanisation (EN1), and relatively high for all sub-indicators except for health malnutrition (H2) showing that for Narok, generally, the focus should be on improving energy productivity.

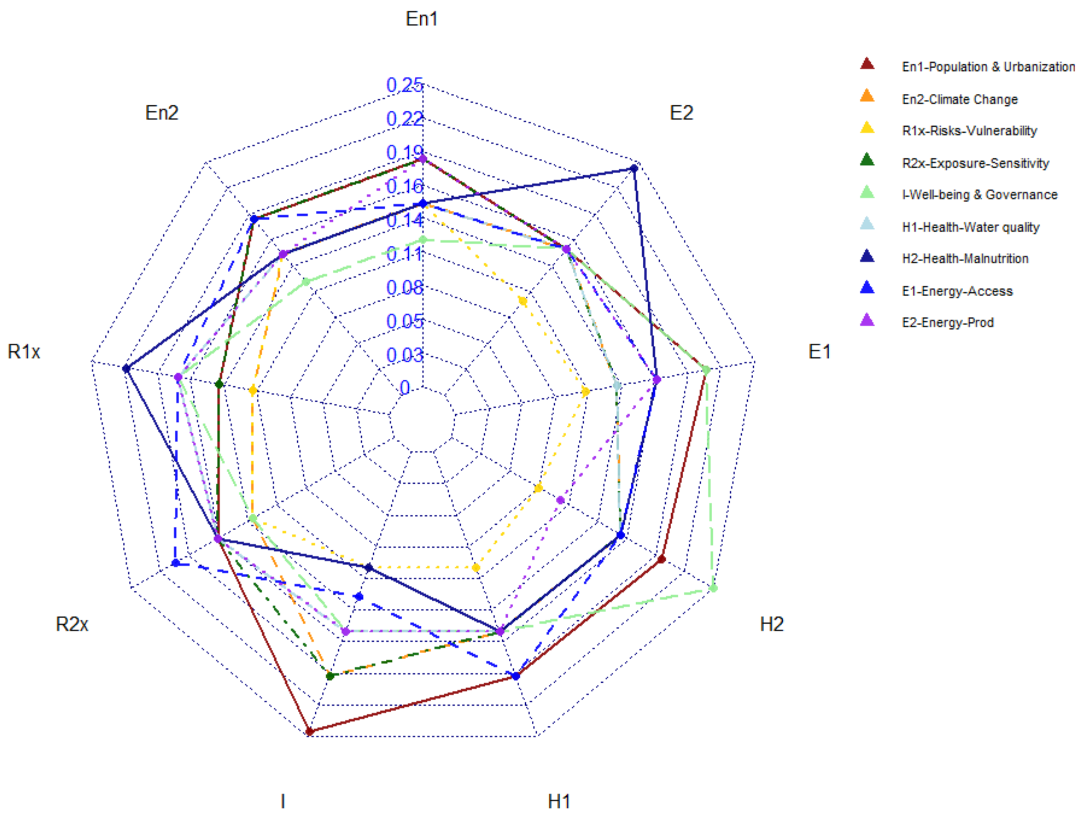

Figure 29. Performance of sustainable indicators against energy indicators – Narok County.

Figure 30. Land degradation in some parts of Narok.

The impacts of energy access (E1) and productivity (E2) on sustainable livelihoods, human health and wellbeing indicators for the Vhembe District Municipality are shown in Figure 31. From the spider chart, the impacts of energy security are less on well-being and governance (I), health-water quality (H1), risks – vulnerability (Rx1), exposure-sensitivity (R2x) and climate change (En2), but relatively higher for population and urbanisation (En1), Health-Malnutrition (H2), energy access (E1) and energy productivity (E2). This implies that there is a need for decisions or policymakers to focus on energy provision to improve the livelihoods of the community and meet the energy demand due to the increasing population and urbanisation trends. Deforestation is one of the major environmental problems identified in the district due to the cutting down of trees for firewood leading to increased soil erosion and degradation. Although there are policies to support the uptake of renewable energy and energy access is high in the district, households still use firewood and other fossil-based fuels to meet their energy requirements and these sources have negative impacts on human health.

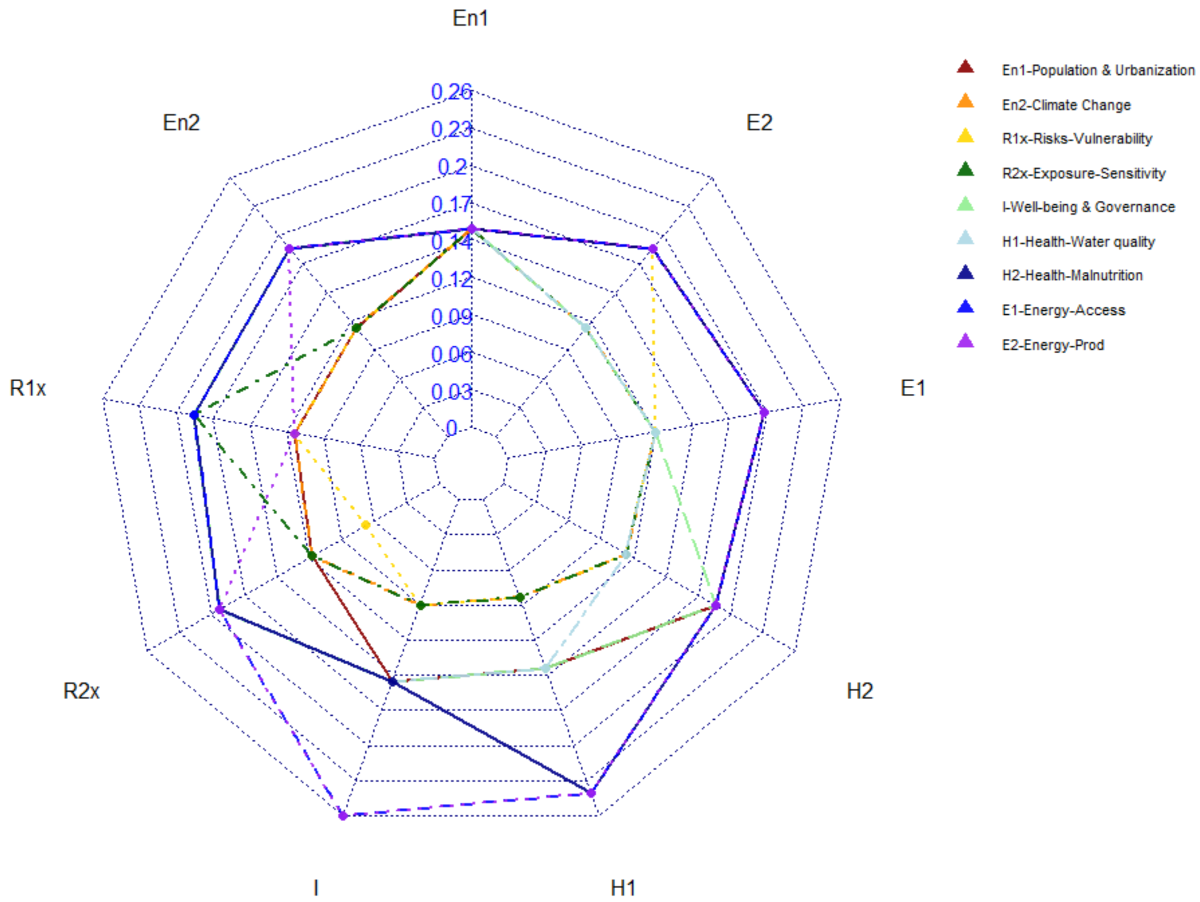

Figure 31. Performance of sustainable indicators against energy indicators – Vhembe District Municipality.

4.3.2.3 Food Security and Sustainable Livelihood Indicators

A pairwise comparison matrix for sustainable livelihood indicators and food security for Narok county is presented in Table 27. The pairwise matrix values for the sustainable livelihood and food security indicators ranged between 0,76 and 1,73. The highest value of 1,73 corresponds to En1/I (population and urbanisation-wellbeing & governance), En2/I (climate change – exposure-sensitivity), and H2/R1x (Health-water quality and climate risks-vulnerability) paired indicators. Similarly, the pairwise comparison matrix for sustainable livelihood indicators and food security for the Vhembe District Municipality ranged between 0,58 and 1,73 (Table 28). The highest value of 1,73 corresponds to the following paired sustainable livelihood indicators: I/En2, I/En2, I/R1x, I/H1, I/H2, H1/En2, H1/R1x, H2/En2, H2/R1x, H2/F1, H2/F2, F1/En2, F1R1x, and F2/En2. These results indicate that for the Vhembe district municipality, food access and productivity are mostly impacted by climate change (En2) and risks and vulnerability (R1x). The lowest value of 0,58 corresponds to the following paired sustainable livelihood indicators: En2/I, En2/H1, En2/H2, En2/F1, En2/F2, R1x/R2x, R1x/I, R1x/H1, R1x/H2, R1x/F1, H1/I, H2/I, F1/H2, and F2/H2. The rest of the pairwise comparison results have a value of 1, suggesting that the paired indicators are almost equally important in the Vhembe District Municipality.

Table 27. Pairwise comparison matrix for sustainable livelihood indicators and food security for Narok county. F1 – Food access and F2 – Food productivity.

	En1	En2	R1x	R2x	I	H1	H2	F1	F2
En1	1,00	1,32	1,32	1,00	1,73	1,32	1,32	1,32	1,00
En2	0,76	1,00	1,00	0,76	1,73	1,32	1,32	1,00	1,32
R1x	0,76	1,00	1,00	1,00	0,76	0,76	0,58	0,76	0,58
R2x	1,00	1,32	1,00	1,00	1,32	1,00	1,00	0,76	1,00
I	0,58	0,58	1,32	0,76	1,00	0,76	1,32	1,32	1,00
H1	0,76	0,76	1,32	1,00	1,32	1,00	1,00	0,76	1,00
H2	0,76	0,76	1,73	1,00	0,76	1,00	1,00	0,76	1,32
F1	0,76	1,00	1,32	1,32	0,76	1,32	1,32	1,00	1,00
F2	1,00	0,76	1,73	1,00	1,00	1,00	0,76	1,00	1,00

Table 28. Pairwise comparison matrix for sustainable livelihood indicators and food security for VDM. F1 – Food access and F2 – Food productivity.

	En1	En2	R1x	R2x	I	H1	H2	F1	F2
En1	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
En2	1,00	1,00	1,00	1,00	0,58	0,58	0,58	0,58	0,58
R1x	1,00	1,00	1,00	0,58	0,58	0,58	0,58	0,58	1,00
R2x	1,00	1,00	1,73	1,00	1,00	1,00	1,00	1,00	1,00
I	1,00	1,73	1,73	1,00	1,00	1,73	1,73	1,00	1,00
H1	1,00	1,73	1,73	1,00	0,58	1,00	1,00	1,00	1,00
H2	1,00	1,73	1,73	1,00	0,58	1,00	1,00	1,73	1,73
F1	1,00	1,73	1,73	1,00	1,00	1,00	0,58	1,00	1,00
F2	1,00	1,73	1,00	1,00	1,00	1,00	0,58	1,00	1,00

The normalization of the PCM for the sustainability livelihood indicators for Narok county is presented in Table 29. The sum of the indices is 1, showing that the indicators are numerically linked and can be analysed as a whole for sustainable development. The CR for the normalized pairwise matrix for Narok county is 0,054, a value lower than 0,10 which shows that the matrix judgments were generated randomly, and the weights calculated are consistent. The results show that the indicators with the highest weights are Population and urbanisation (En1), Food production (F2), and Health-water quality (H1). Climate change (En2) and Food access (F1) also showed higher weights (Table 9). The highest mean score is for Population and urbanisation (En1) indicating a greater impact on livelihood compared to the other indicators. For Narok county, the demand for food production is increasing with population growth and urbanisation, affecting food security and livelihood the most. Pastoralists are some of the vulnerable people in Narok hence there is a need to provide them with information and build their capacity to diversify their livelihood activities so that they are more resilient to climatic and non-climate changes in their community. Overall, the integrated composite index for Narok county is 0,11, classifying the county into a lowly sustainable livelihood category (Table 29).

For the Vhembe district municipality (Table 30), the results show that the indicators with the highest weights are well-being and governance (I), Health-Malnutrition (H2), and Food access (F1). The highest mean score is for well-being and governance (I) indicating a greater impact on livelihood compared to the other indicators. As shown in Table 30, climate change (En2) and well-being and governance (I) impact food access and productivity the most. Overall, the integrated composite index for Vhembe district municipality is 0,11, classifying the county into a lowly sustainable livelihood category (Table 30).

Table 29. Normalized pairwise comparison matrix, consistency ratio (CR) and composite index for sustainable livelihood indicators and food security for Narok county.

	En1	En2	R1x	R2x	I	H1	H2	F1	F2	index
En1	0,136	0,155	0,112	0,113	0,167	0,139	0,137	0,152	0,109	0,135
En2	0,103	0,118	0,085	0,086	0,167	0,139	0,137	0,115	0,143	0,121
R1x	0,103	0,118	0,085	0,113	0,073	0,080	0,060	0,088	0,063	0,087
R2x	0,136	0,155	0,085	0,113	0,127	0,106	0,104	0,088	0,109	0,114
I	0,078	0,068	0,112	0,086	0,096	0,080	0,137	0,152	0,109	0,102
H1	0,103	0,090	0,112	0,113	0,127	0,106	0,104	0,088	0,109	0,106
H2	0,103	0,090	0,148	0,113	0,073	0,106	0,104	0,088	0,143	0,107
F1	0,103	0,118	0,112	0,149	0,073	0,139	0,137	0,115	0,109	0,117
F2	0,136	0,090	0,148	0,113	0,096	0,106	0,079	0,115	0,109	0,110
CR = 0,054										∑ = 1
Composite integrated index (weighted average)										0,111

Table 30. Normalized pairwise comparison matrix, consistency ratio (CR) and composite index for sustainable livelihood indicators and food security for VDM.

	En1	En2	R1x	R2x	I	H1	H2	F1	F2	index
En1	0,111	0,079	0,079	0,117	0,137	0,113	0,124	0,113	0,107	0,109
En2	0,111	0,079	0,079	0,117	0,079	0,065	0,072	0,065	0,062	0,081
R1x	0,111	0,079	0,079	0,067	0,079	0,065	0,072	0,065	0,107	0,081
R2x	0,111	0,079	0,137	0,117	0,137	0,113	0,124	0,113	0,107	0,115
I	0,111	0,137	0,137	0,117	0,137	0,195	0,215	0,113	0,107	0,141
H1	0,111	0,137	0,137	0,117	0,079	0,113	0,124	0,113	0,107	0,115
H2	0,111	0,137	0,137	0,117	0,079	0,113	0,124	0,195	0,186	0,133
F1	0,111	0,137	0,137	0,117	0,137	0,113	0,072	0,113	0,107	0,116
F2	0,111	0,137	0,079	0,117	0,137	0,113	0,072	0,113	0,107	0,109
CR = 0,032										∑ = 1
Composite integrated index (weighted average)										0,111

Figure 32 depicts results for impacts of food security (food accessibility F1 and productivity, F2) on sustainable livelihoods, human health and wellbeing indicators. Based on the spider chart, the impacts of food security as accessed by accessibility indicator are more pronounced across most sustainable livelihoods, human health and wellbeing indicators. In particular, food accessibility impacts are fairly high for the following indicators: climate exposure-sensitivity (R2x) and health-water quality (H1), health-malnutrition (H2) and notable low for wellbeing and governance (I). Food productivity impacts are comparatively high for climate risk-vulnerability (R1x), health-water quality (H1), and population and urbanisation (En1) and low for health-malnutrition (H2) and climate change (En2).

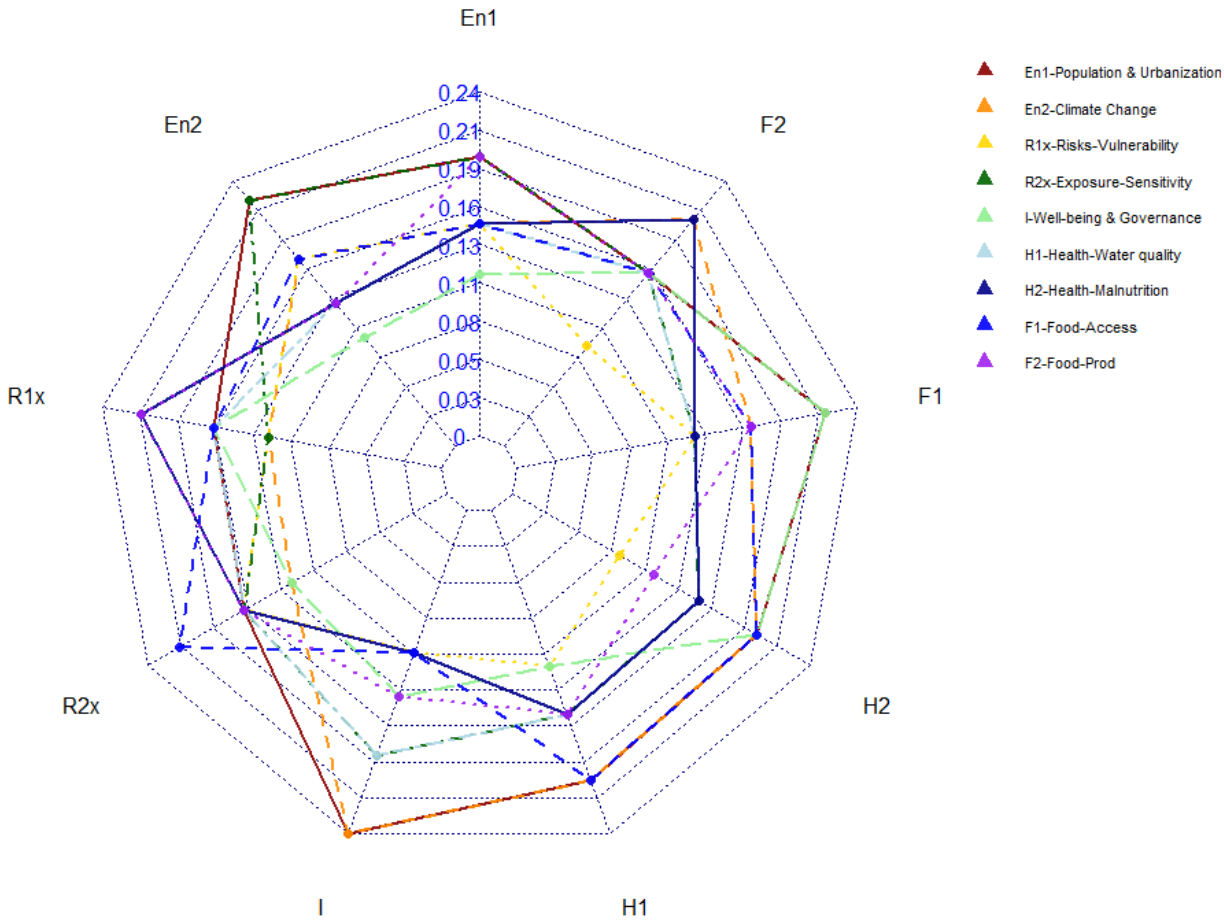

Figure 32. Performance of sustainable indicators against Food security indicators – Narok County.

The impacts of food accessibility and productivity on sustainable livelihood indicators for the Vhembe district municipality are depicted in Figure 33. Food accessibility impacts are specifically high for the following indicators: well-being and governance (I), climate change (En2), and climate risk-vulnerability (R1x), and notably low for health-malnutrition (H2). Likewise, food productivity impacts are relatively high for climate change (En2), well-being and governance (I), and climate exposure-sensitivity (R2x). Health-Malnutrition (H2) is one of the most impacted sustainable livelihood indicators by food access (F1) and food productivity (F2) as shown in Table 30 and Figure 33.

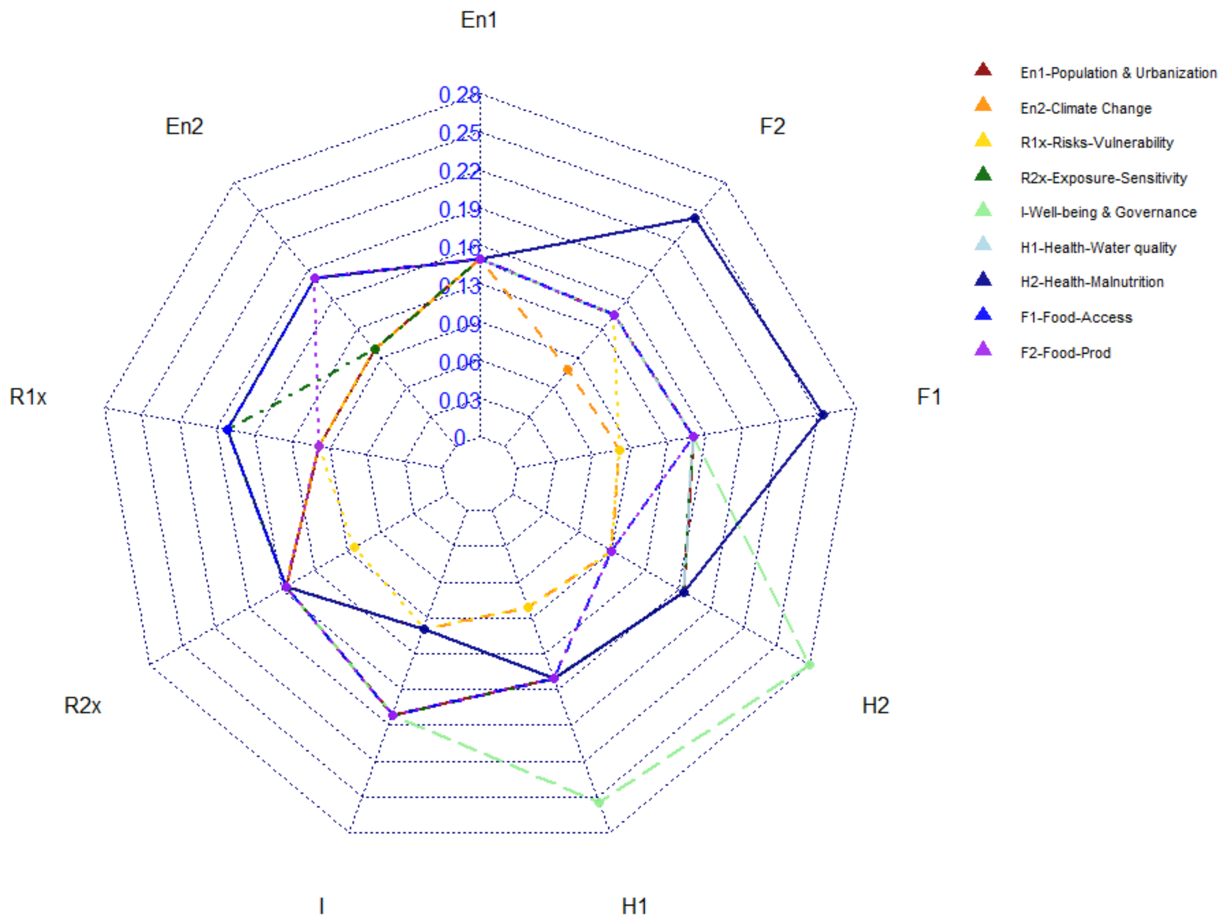

Figure 33. Performance of sustainable indicators against Food security indicators – Vhembe District Municipality.

4.3.3. Assessment of the Linkages Between WEF Resources and Sustainability Livelihood Indicators

Correlation analysis was undertaken to determine how the WEF resources are linked to sustainable livelihood indicators. In particular, the association between the WEF nexus and sustainable livelihoods constructs has been computed using their respective composite weights. As given in Figure 34 the correlation (at p-value =0,05) between the sustainable livelihood indicators and the WEF nexus resources in Narok County, is generally dispersed with the following notable inferences:

a) There exists a strong positive (and significant) correlation between the present and future agricultural production and the impact of weak governance institutions on the general well-being of communities (F2-I: ρ~0,83) as well as the high exposure to the limited WEF nexus resources attributed to the present and future drivers of economic, and socio-economic changes in the communities (F2-R1x: ρ~0,57).

b) A strong significant positive correlation exists between water use for irrigation and the risks and vulnerabilities experienced by communities due to the changes in the present and future environmental and socio-economic conditions (E2-R2x: ρ~0,69).

c) The present and future access to enough, nutritive food by communities are positively (and significantly) correlated to the well-being of communities due to the weak government governance (F1-I: ρ~0,76).

d) The energy productivity (in the context of spurring economic growth) in Narok County is negatively (yet significant) correlated to the unsafe water, sanitation and general hygiene of the communities (E2-H1: ρ~-0,69).

Similarly, based on results presented in Figure 35, the correlation (at p-value =0,05) between the sustainable livelihood indicators and the WEF nexus resources in Vhembe District Municipality, exhibits the following features:

a) A strong positive (and significant) correlation is observed between agricultural productivity (F2) and the following indicators: food security (accessibility; F1), energy production (E2), water access (W1), climate change risk-vulnerability (R2x) and greater exposure and sensitivity (R1x).

b) Food security (F1) depicts a strong positive correlation with energy production, water access, risk-vulnerability as well as and greater exposure and sensitivity.

c) There exists a strong significant positive correlation between energy productivity and water access (0,99), as well as health and water quality (0,74). In general, energy productivity is positively correlated with all livelihood indicators, although the correlation across most of the indicators is non-significant.

d) Water accessibility is strongly correlated with health and water quality (0,73). Similarly, the water indicator is positively correlated with most of the livelihood indicators, however only R2x and H1 depict a significant positive correlation.

Overall, the WEF nexus and sustainable livelihoods indicators correlation results corroborate those reported by, e.g. Laspidou, et al., (2019) and Wolde et al. (2022), thereby establishing the inherent association between the sustainable livelihood indicators and the WEF nexus resources. This demonstrates that sustainable WEF nexus resource utilization will inadvertently translate to sustainable livelihoods, health and well-being of the community. In a bid to determine the nature of the causal relationships between the WEF nexus resources and the sustainable livelihood indicators, Structural Equation Modelling is being considered. This is especially true given that the research is nascent and therefore the analysis will be exploratory, in accordance with the argument advanced by, e.g. Henseler, et al. (2016), averring that the Partial Least Squares-Structural Equation Modelling (PLS-SEM) methodology is duly suited in less developed research areas.

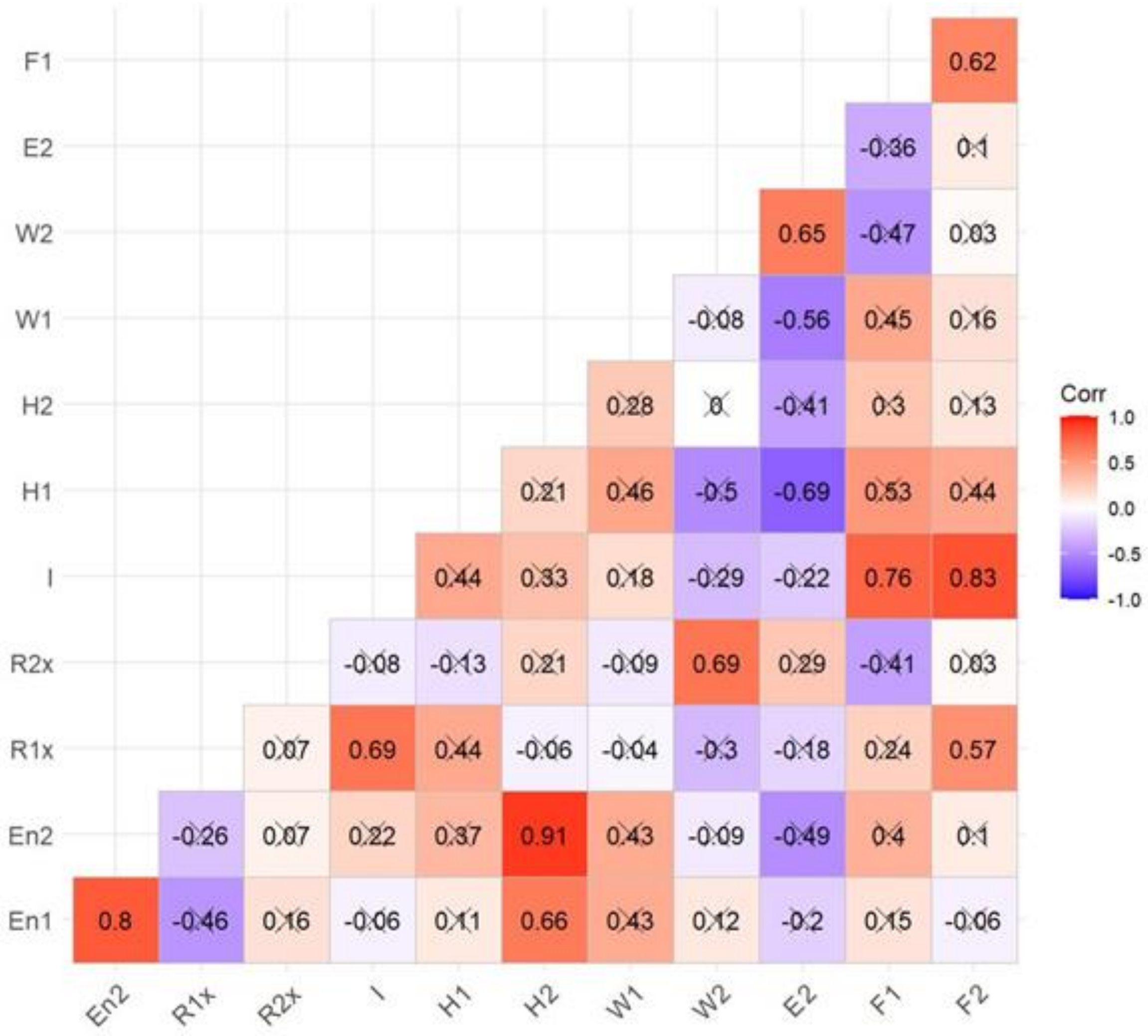

Figure 34. Correlation matrix for the composite weights of sustainable livelihood indicators and the WEF resources across Narok County.

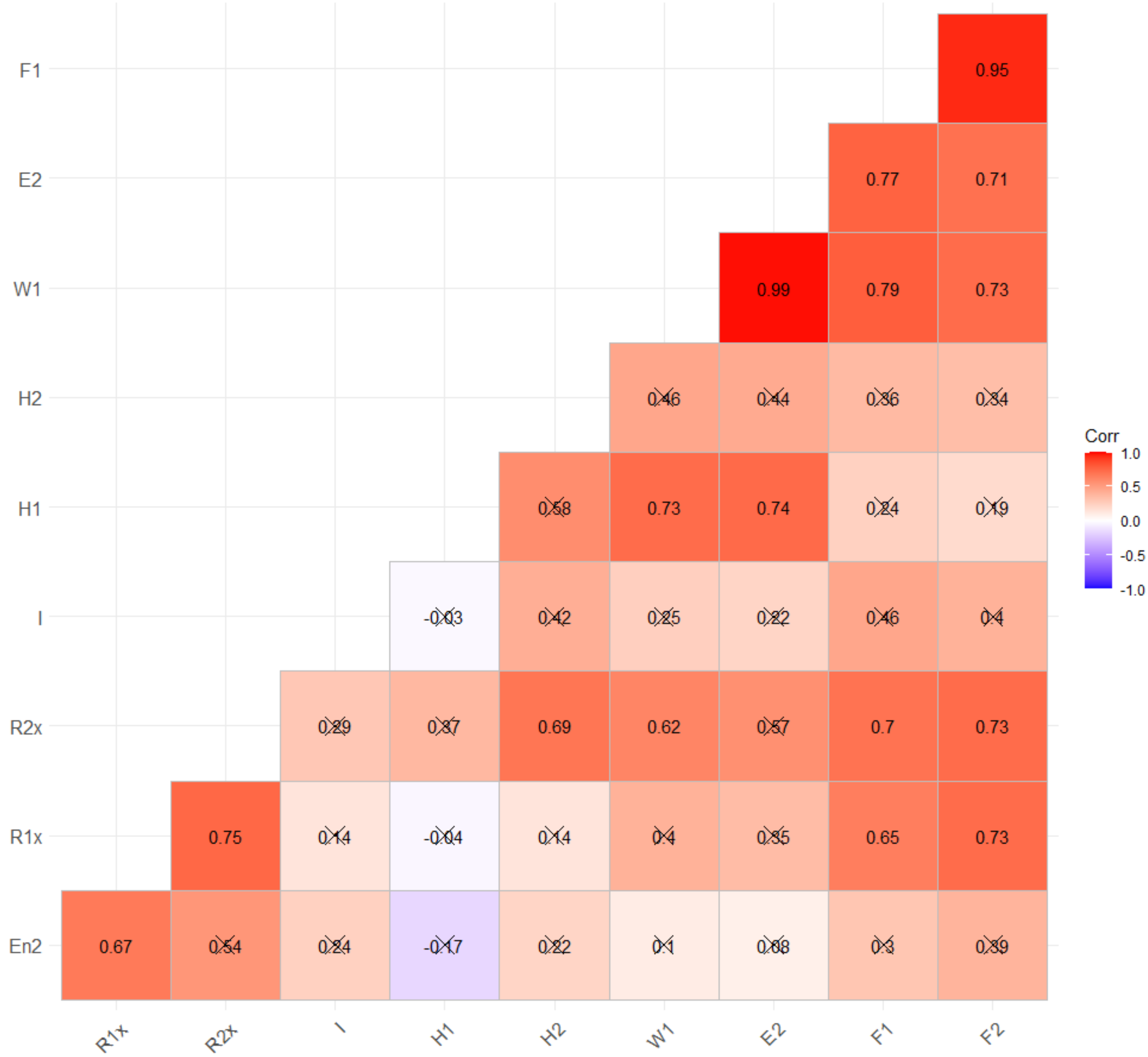

Figure 35. Correlation matrix for the composite weights of sustainable livelihood indicators and the WEF resources across Vhembe District Municipality.

4.4. Concluding Remarks

The study identified indicators that highlight the interactions between the WEF nexus components and their impact on livelihoods, health and wellbeing from literature and based on the stakeholder surveys that were carried out in Narok County and the Vhembe District Municipality. The study assessed the linkages of the sustainable indicators and the impact that the WEF components have on them. The results showed that the WEF components play a critical role in the improvement of people's livelihoods, health and wellbeing. Furthermore, population and urbanisation came out strongly as an aspect that impacts water, energy and food and consequently influences livelihoods, health and wellbeing of the community. Population growth and increased urbanisation have also had impacts on the environment as evidenced by land degradation, water pollution and deforestation that also impact the livelihoods, health and wellbeing of communities in the county. Discussions with participants also highlighted that Narok is highly vulnerable to climate change and some notable changes observed include an increase in intense storms that cause flooding, droughts, an increase in pests and diseases affecting crops and changes in the onset of the rainfall season. Stakeholders such as government departments, civil society and communities require information and support to make coordinated and integrated decisions that promote the achievement of sustainable development goals. Water, energy and food components, therefore, need to be managed well to withstand the threats from socioeconomic as well as climatic drivers as these also impact the sustainability of livelihoods in the county.

5. WEF NEXUS MODEL FOR SCENARIO PLANNING AND ASSESSING SDG PERFORMANCE

5.1. Introduction

The Water-Energy-Food (WEF) nexus research places a strong emphasis on understanding the complex dynamic relations between water, energy and food domains. These are some of the key resources that affect the achievement of global and national sustainable development, including the goals endorsed to end poverty and hunger, overcome climate change, and access clean energy and clean water and sanitation, among others (Frades et al., 2020). The nexus research also highlights cross-cutting challenges the three resources contribute to and are influenced by numerous factors including climate change and variability, poverty, inequality and resource security, among others. For instance, the projected population growth rate in Africa by 2050 is likely to pressurise the already depleted resources, with the demand exceeding supply (Vörösmarty et al., 2005; Naidoo et al., 2021).

The livelihoods of the greater population, particularly those living in the rural areas, where natural systems dominate, are expected to be affected due to a reduction in rainfall and food production in the same projected period (Mabhaudhi et al., 2019; Nhamo et al., 2021). Rainfall uncertainty will likely exacerbate water stress by 2050, affecting between 350-600 million people in Africa (Barros et al., 2014). With Africa considered the most vulnerable continent to climate change, experiencing frequent climate-related impacts (Hoegh-Guldberg et al., 2018; Scholes and Engelbrecht, 2021), the need to understand the relationships between the three WEF resources and how these will be impacted in the future cannot be overemphasized. Such knowledge plays a significant role in the development of WEF nexus tools which can enable vulnerable communities to proactively develop resource planning and management strategies, build adaptation capacity and harmonize economic growth, social inclusion and environmental protection for sustainable development.

Scenario analysis is one of the proven, popular and flexible tools that can be used to address this objective (Mander et al., 2008). Scenario planning enables a pathway to evaluate plausible future conditions and inherent processes through which such conditions might emerge (Rounsevell and Metzger, 2010). In particular, scenario planning allows decision-makers to identify ranges of possible outcomes and impacts, appraise responses and manage for both positive and negative feasibilities. While scenario planning appears to be a promising tool to explore the future, and to improve capacity, in relation to long-term integrative planning across nexus spheres, so far, the tool has been applied to only isolated resource domains, such as in energy (Foxon, 2013), food (Bows et al., 2012) and water (van Vliet and Kok, 2015). Few studies have also applied scenario planning on two of the nexus components, e.g. renewable energy generation and water (Macknick et al., 2012). Although scenario planning analysis is yet to be fully tested in complex research fields such as the WEF nexus, the tool's worth has been proven valuable in related research fields such as integrated water management (Hatzilacou, et al., 2007) and environmental management (Reed et al., 2013). For this purpose, the current study aims to develop scenarios planning to evaluate plausible ranges of outcomes and their potential impacts on sustainable development, to support resource management and planning and build adaptation capacity at a local level, focusing on Vhembe District Municipality, South Africa and Narok County in Kenya.

5.2. Linkages Between WEF Nexus Resources and Sustainable Development Goals

5.2.1. Literature Review

Achieving adequate WEF resource security for all while preserving the environment is the unbreakable cornerstone of the WEF nexus (Liu et al., 2018), the value of which lies in its capacity to highlight the normative implications of uncoordinated decision-making and management of competing resources in the WEF sectors required to achieve SDGs (Johnson and Karlberg, 2017). The ability to "meet the needs of the present without compromising the ability of future generations to meet their own needs" is a widely accepted definition of sustainability, first articulated by the Brundtland Commission (Brundtland, 1987). A better understanding of the sustainability concept provides the basis for addressing and solving competing socio-economic and environmental issues that threaten to undermine the welfare of people all over the world (Emina, 2021). The attainment of SDG goals is the blueprint for achieving better and more sustainable future for all, starting today. According to the Sustainable Development Goals Report 2022, cascading and interlinked crises dominated by the COVID-19 pandemic, climate change, and conflicts threaten the 2030 Agenda for Sustainable Development and humanity's survival. The confluence of crises, affects food and nutrition, health, education, the environment, and peace and security (SDGs). In an attempt to reverse the impacts and work toward SDGs attainment, the adoption of the WEF nexus approach becomes key. However, as demonstrated by the global annual distribution of the scientific publication in Figure 36, the research on the WEF nexus approach and SDGs is still in its infancy. Figure 36 depicts that between 2015 and 2022, there has been a steady increase in the number of publications, from 2 to 18.

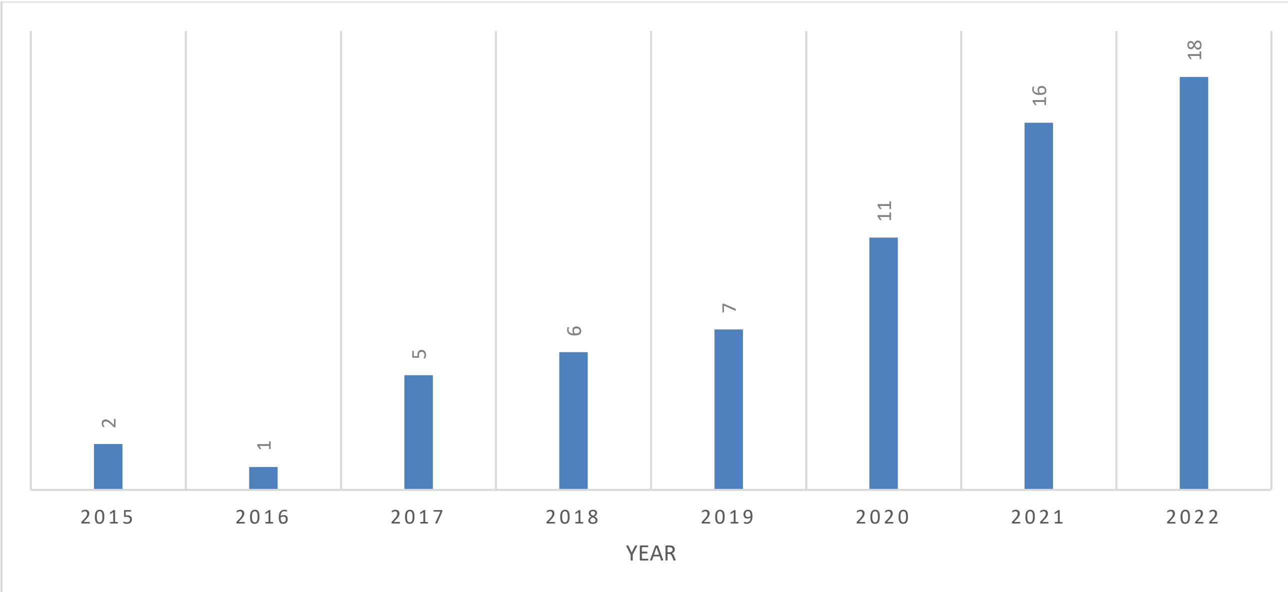

Figure 36. Distribution of annual publications.

As illustrated in Figure 37, various countries have contributed to the body of knowledge on the WEF nexus and sustainable development goals, with South Africa taking the second lead among the top six countries. The identified leading countries are ranked according to the nationality of the respective author. Publication in Africa is through Single Country Publication (SCP), which reflects intercountry collaboration. To avoid siloed approaches, South African authors will need to collaborate more with other countries. In assessing the pattern in publication productivity, it can be noted that Multiple Country Publications (MCP) are still lagging in comparison to SCP. The observed gaps will be addressed by intercountry collaborations.

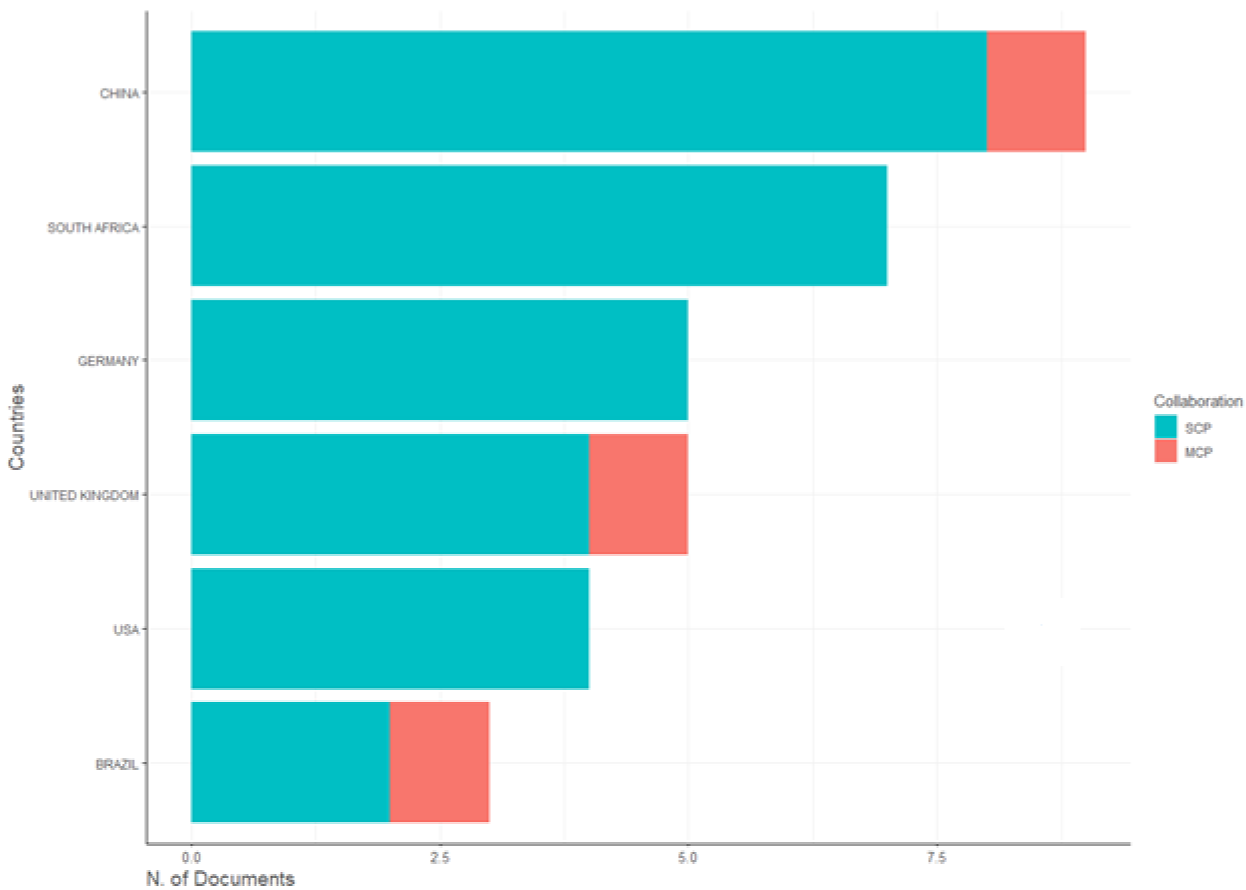

Figure 37. Top six countries that have contributed to the body of knowledge on the WEF nexus and Sustainable development goals, through either Single Country Publication (SCP) or Multiple Country Publication.

The analysis of the frequent occurrence of keywords in published WEF nexus and sustainable development goals is depicted in Figure 38. There are four observed clusters, with the yellow cluster encompassing aspects of WEF resources including water, energy, food and food security. The blue cluster is one of the most dominant clusters with more frequent words relating to sustainable development, and the requirements in the planning and management of resources required in the decision-making. The green cluster focuses on sustainable development goals, resource usage, drivers and the number of people affected. The green cluster also talks about the WEF nexus idea, which shows how important it is to apply a holistic and integrated WEF nexus approach to achieve the 2030 SDGs.

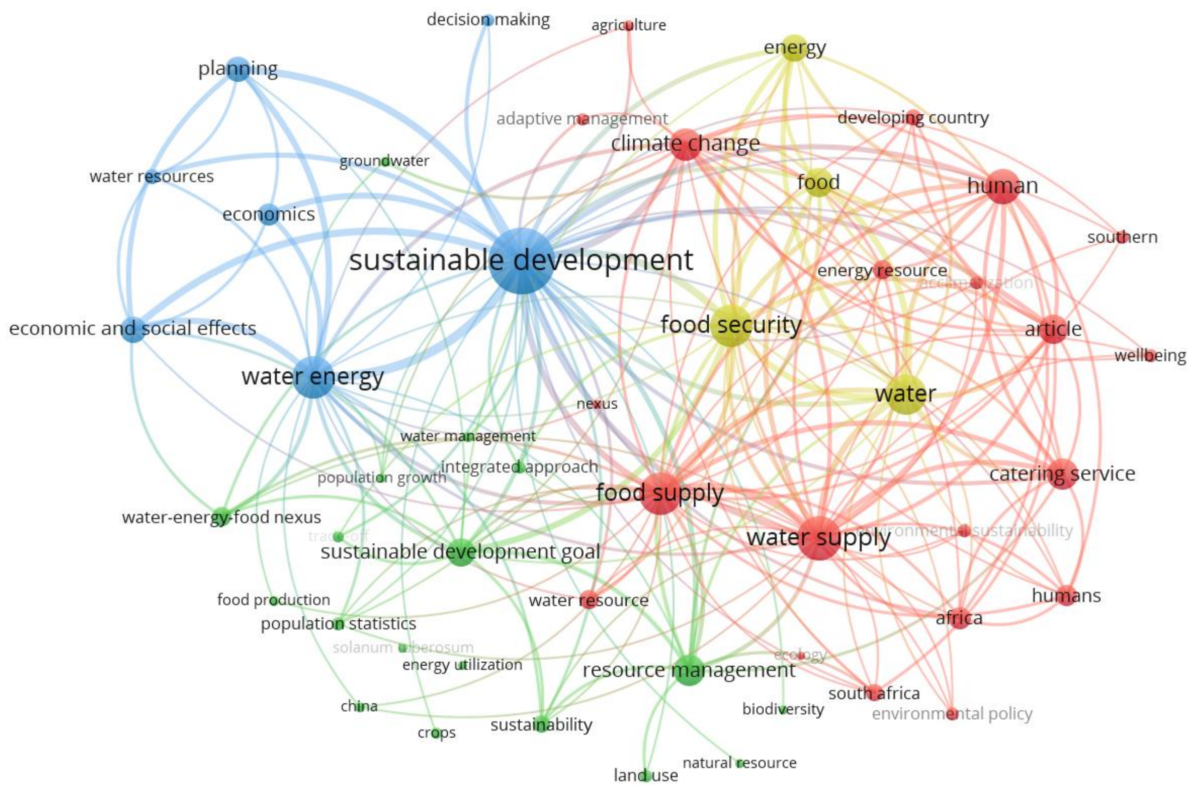

Figure 38. Frequent occurrence of keywords in published WEF nexus and sustainable development goals published scientific papers.

Table 31, provide the SDG targets (15 of the 17), their respective descriptions and their corresponding domains in the environment, social and economic pillars with links to WEF Nexus resources. Some of the targets correspond to a single SDG target, while others are a combination of multiple SDG targets. Due to existing interconnections, the achievement of SDG targets has significant effects on each pillar of the WEF nexus (Liu et al., 2018). According to the work by Malagó et al. (2021), if all selected SDG targets are met, each pillar of the nexus should be in equilibrium with the others.

Table 31. Description of selected SDGs and the corresponding domains which have links to the WEF nexus resources. Adapted from Malagó et al. (2021)

SDG targets	Domains	Description
Decrease inequality and reduce poverty (SDG 1/ SDG 4/SDG 5/SDG 10)	Economy /Society	Guarantee inclusive, equitable quality education and learning opportunities for all (decrease all gender and other inequalities)
Food security and livelihoods (SDG 2.1/2.2/2.3)	Society	End hunger, end all forms of malnutrition and ensure food for all people, with particular attention to the poorest and infants
Human well-being (SDG 3.9)	Economy /Society	Promote well-being and guarantee healthy lives
Water supply (SDG 6.1)	Economy/ Environment/Society	Achieve universal and equitable access to safe and affordable drinking water for all
Sanitation (SDG 6.2)	Economy /Society	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
Water quality (SDG 6.3)	Economy/ Environment/Society	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
Water efficiency (SDG 6.4)	Economy/ Environment/Society	Increase water use efficiency and ensure freshwater supply. In particular, this target addresses the issue of water scarcity and the importance of increasing water-use efficiency
Energy supply (SDG 7.1)	Economy/ Environment/Society	Ensure universal energy access (i.e. access to electricity) to affordable, reliable and modern energy services
Energy efficiency and increased share in renewables (SDG 7.2, SDG 7.3, /7a and b)	Economy/ Environment	Increase substantially the share of renewable energy in the global energy mix thus taking urgent action to combat climate change and its impact. Ensure access to affordable, reliable, sustainable, modern and clean energy services improving the efficiency. In particular, facilitate access to renewable energy and cleaner fossil fuel technology
Employment opportunities (SDG 8.2/8.3/8.5/ 8.9)	Economy/ Environment/Society	Promote sustainable economic growth in accordance with national circumstances, achieving higher levels of economic productivity through e.g. technological upgrading. Promote employment and decent work for all and promote sustainable tourism
Resource use efficiency (SDG 8.4/12.2)	Economy/ Environment/Society	More efficient use of resources in terms of consumption and production (e.g. reduce ecological footprint)
Reducing waste (SDG 12.5)	Economy/ Environment	Substantially reduce waste generation through prevention, reduction, recycling and reuse
Climate resilience (SDG 13.1)	Economy/ Environment/Society	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters
Conserve and sustainably use the oceans, seas and marine resources (SDG 14.1)	Environment	Prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution
Protect and restore terrestrial ecosystems (SDG 15.1/15.3/15.5)	Environment	Ensure the conservation, restoration and sustainable use of terrestrial and inland ecosystems, combat desertification, and take urgent action to reduce the degradation of natural habits

5.2.2. Assessing the Linkages Between Sustainable Development Goals and Water, Energy, Food and Ecosystem Resources using Case Studies

Underpinned by the postulates reported in Malagó et al. (2021), an analytical framework premised on the Water, Energy, Food and Ecosystem nexus and the SDGs linkages has been used to assess the inherent interconnections using three WEF nexus case studies in South Africa, (viz, Nhamo et al.; 2020a, Mabhaudhi et al.; 2019 and Mabhaudhi et al, 2021). All the case studies considered viewed the WEF nexus as either a tool that could be used to assess the attainment of SDGs or for livelihood assessment. On the analytical framework, two matrices were derived, i.e.

a) an excerpt of the WEFE matrix reported in Malagó et al. (2021) – this nexus matrix links the WEFE resources to thirteen of the SDGs targets given in Table 31. This matrix is presented in Table 32.

b) The SDG matrix: this matrix was derived from the three case studies. In this regard, the three case studies were synthesised to establish if the reported studies demonstrated that achievements of the considered SDG targets would have impacts on the Economy (Ec), Environment (En) and Society (So). In the assessment, each study was evaluated and assigned a score of -1, 0, 1 corresponding to "study does not allude to an impact", "no linkage to SDGs" and "the study alludes to potential impact." The scores were assigned independently by the research team and other external experts and then compared. Through analysis, the scores that had the highest agreement were accepted, thereby forming “the case study matrix”, given in Table 33.

The interconnection between the WEFE pillars and the SDG targets was determined to be the aggregation of “dot product” between each WEFE pillar and SDG target. The results were then rescaled to between 0 and 100, measuring the magnitude of interconnection between SDG targets and WEFE pillars. The results of the SDG impacts on the Economy, Environment and Society as well as their interconnectedness with WEFE pillars are visualized using polar plots, see Figure 39 to Figure 44. A score of 0 indicates the absence of interconnection between SDG targets and WEFE pillars, while 100 indicates a maximum interconnection with the particular nexus pillar.

Table 32. The Nexus Matrix weighting the WEFE nexus interconnections linking each pillar to each SDG target

SDG targets	Water	Energy	Food	Ecosystem
sdg_1_4_5_10	3	3	3	1
sdg_2.1_2.2_2.3	2	2	3	1
sdg_3.9	2	1	2	2
sdg_6.1	3	2	1	1
sdg_6.2	3	2	1	2
sdg_6.3	3	1	1	3
sdg_6.4	3	3	2	2
sdg_7.1	2	3	2	1
sdg_7.2_7.3	2	3	2	3
sdg_8.2_8.3_8.5_8.9	2	3	2	2
sdg_8.4_12.2	2	2	3	3
sdg_12.5	3	3	3	3
sdg_13.1	2	2	2	3

Table 33. The SDG matrix derived from the case study matrix

SDG Targets	**Economy**			**Environment**			**Society**		
	Case study 1	**Case study 2**	**Case study 3**	**Case study 1**	**Case study 2**	**Case study 3**	**Case study 1**	**Case study 2**	**Case study 3**
sdg_1_4_5_10	0	0	-1	0	0	-1	0	0	-1
sdg_2.1_2.2_2.3	1	1	1	1	1	1	1	1	1
sdg_3.9	1	0	1	0	0	1	1	0	1
sdg_6.1	1	0	1	0	0	1	1	0	1
sdg_6.2	0	0	1	0	0	1	0	0	1
sdg_6.3	0	0	1	0	1	1	1	0	1
sdg_6.4	-1	1	1	1	1	1	1	1	1
sdg_7.1	1	1	1	1	1	1	1	1	1

SDG Targets	Economy			Environment			Society		
	Case study 1	Case study 2	Case study 3	Case study 1	Case study 2	Case study 3	Case study 1	Case study 2	Case study 3
sdg_7.2_7.3	-1	0	0	-1	0	1	-1	1	1
sdg_8.2_8.3_8.5_8.9	-1	0	0	-1	0	-1	-1	0	0
sdg_8.4_12.2	0	1	1	0	1	1	1	0	1
sdg_12.5	-1	0	0	0	0	0	-1	0	0
sdg_13.1	1	1	1	1	1	1	1	1	1

Analysis of the interconnectedness between the WEFE pillars and SDGs targets based on case study one, given in Figure 39, illustrates that the water and food resources exhibit high interlinkages with SDGs while the energy sector exhibits subtle. As shown in Figure 40, case study two demonstrated that the food and water sector have average interconnection to SDGs while energy has maximum interconnection. It is surprising to note that in both case studies one and two, the ecosystem resources lack noticeable linkages to the SDGs. The water and ecosystem pillars exhibit high levels of interlinkages to the SDG targets while the linkage between the energy resources to the SDGs is subtle, see Figure 44. These varying degrees of interlinkages between the WEFE pillars and SDGs across the case studies could be attributed to the inherent differences in the object of the study.

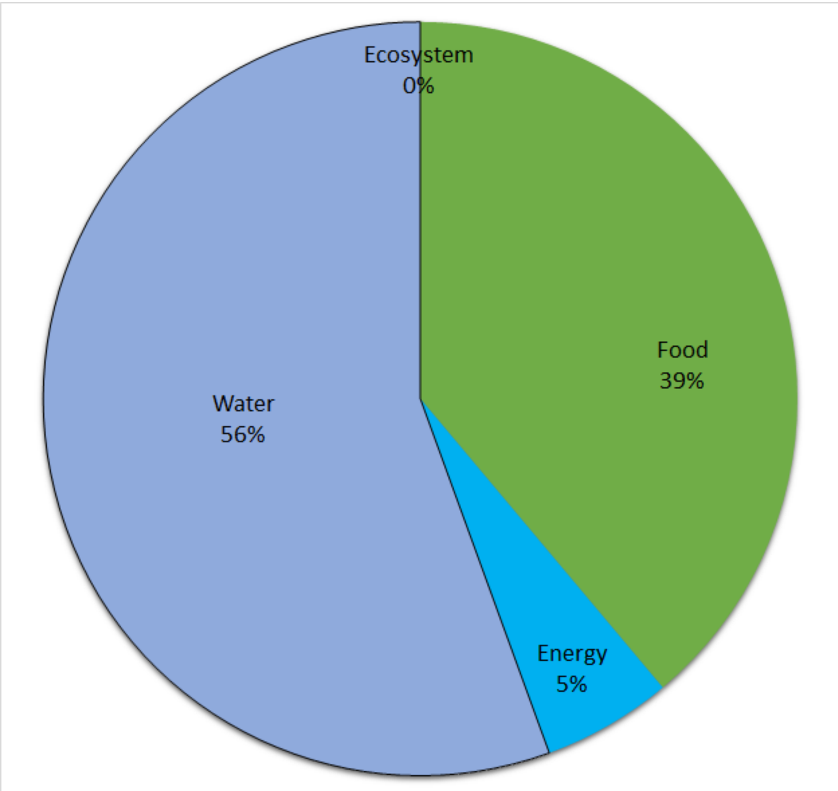

Figure 39. WEFE and SDGs interconnections. Case study 1.

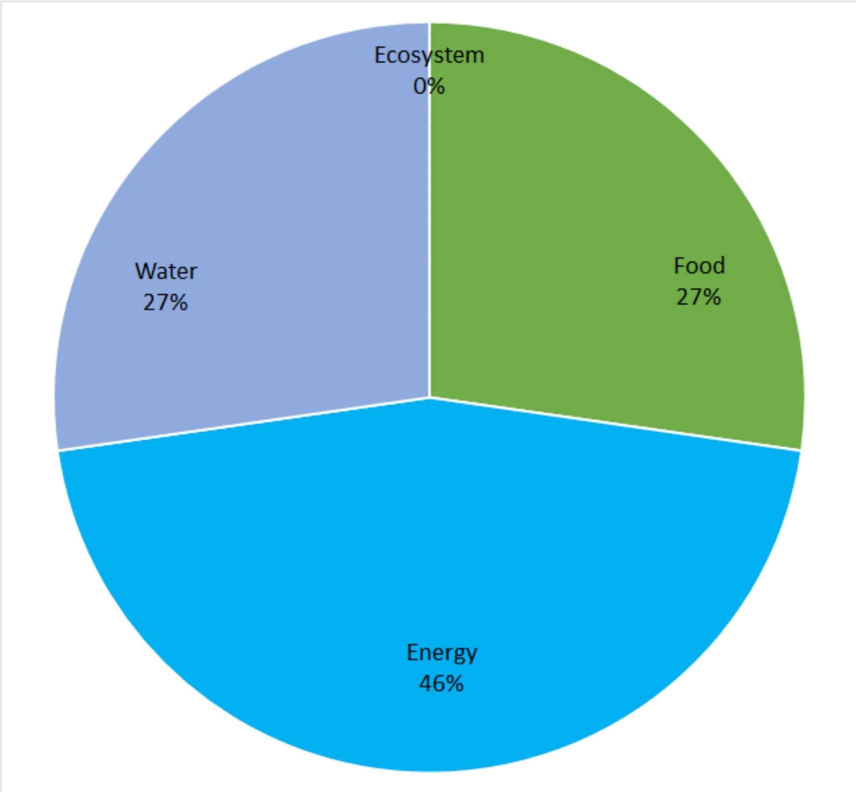

Figure 40. WEFE and SDGs interconnections. Case study 2.

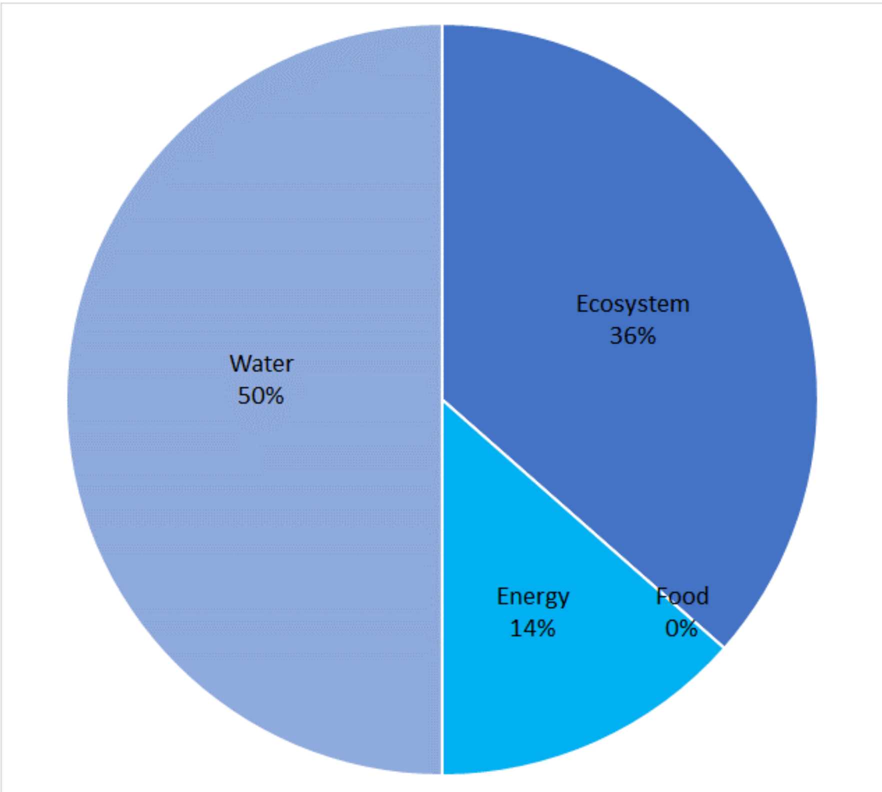

Figure 41. WEFE and SDGs interconnections. Case study 3.

From the perspective of the potential impacts the SDGs targets have on the economy, environment and society, the reviewed case studies demonstrated varying degrees. As shown in Figure 42, case study one demonstrated subtle impacts (at a scale of < 50%), on only the environment (~ 23%) and society (~49%). The low values could be attributed to the focused scope of the study, i.e. "to assess rural livelihoods, health, and well-being in southern Africa, recommending tailor-made adaptation strategies for the region aimed at building resilient rural communities, Mabhaudhi, et al., 2019." In contrast, case studies two and three demonstrated that the SDGs have higher impacts on society, the economy & environment (~80%).

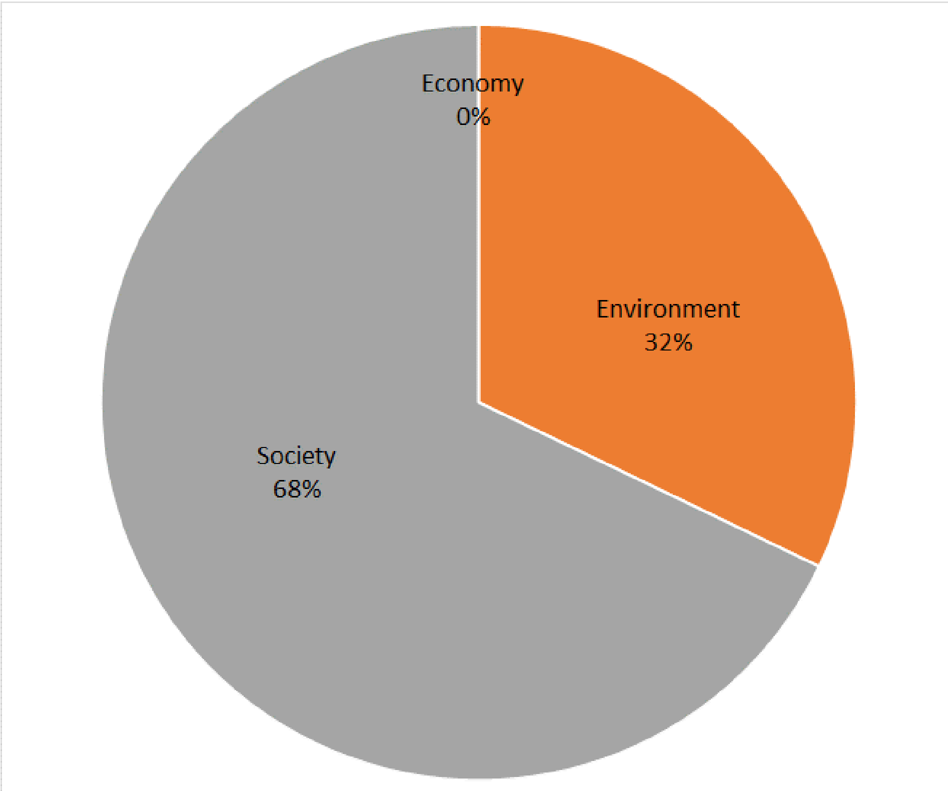

Figure 42. Impacts of SDGs achievements on the Economy, Environment and Society. A synthesis of study case 1.

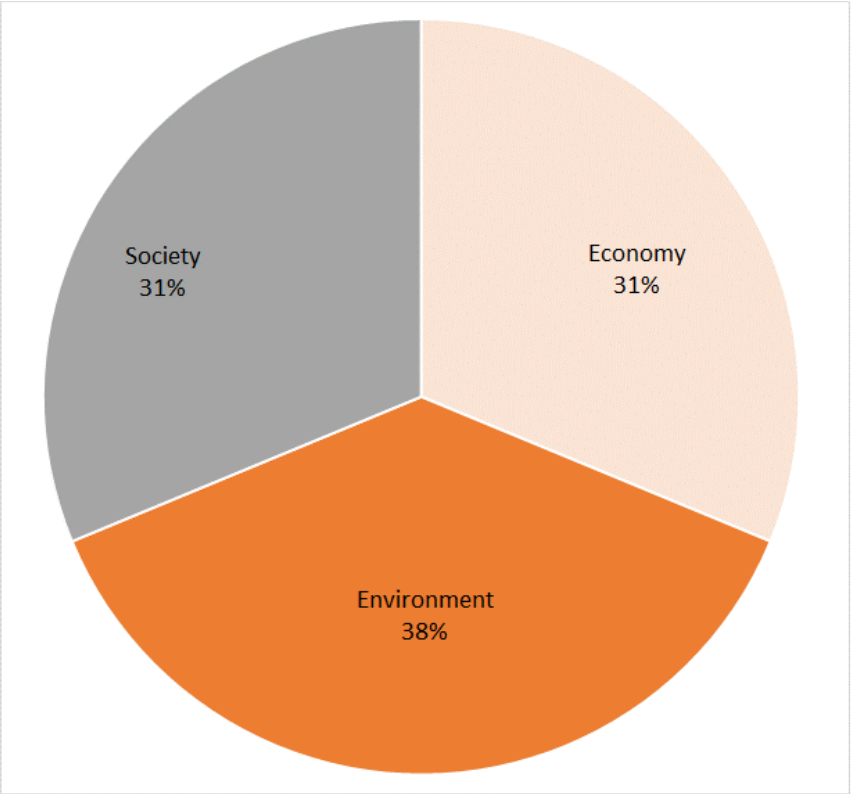

Figure 43. Impacts of SDGs achievements on the Economy, Environment and Society. A synthesis of study case 2.

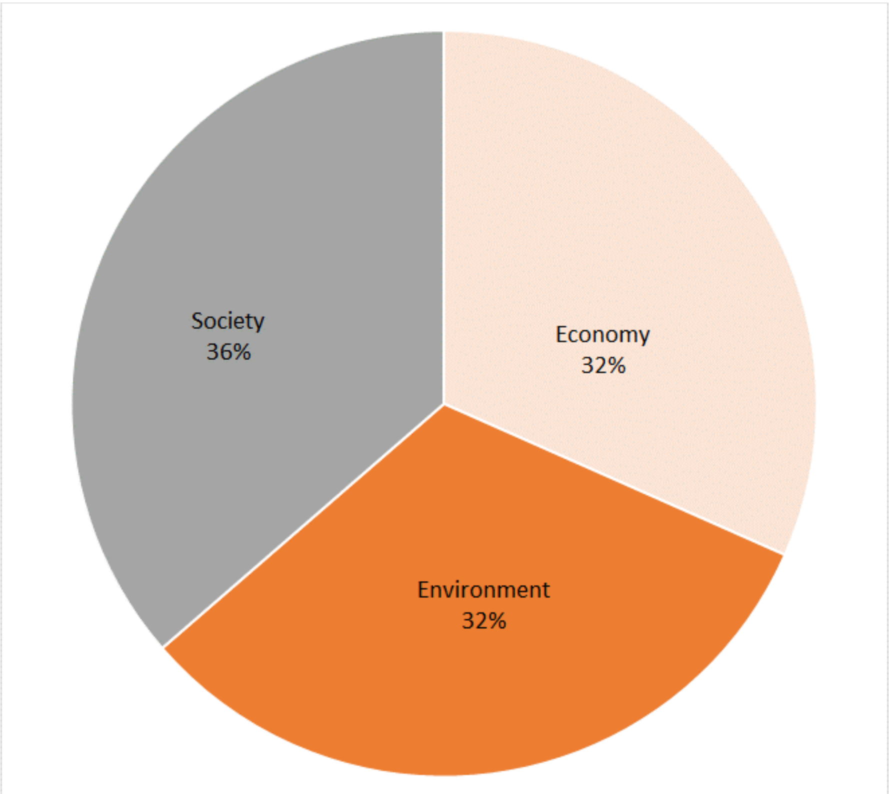

Figure 44. Impacts of SDGs achievements on the Economy, Environment and Society. A synthesis of study case 3.

5.3. Scenario Planning Development

Scenario planning is considered a reliable approach to evaluate the future characteristics and uncertainties thereof. In a simplified definition, scenarios are "*stories about the future*" (Heugens and Van Oosterhout (2001), or in detailed "*plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships*" Scenario planning are conducted based on qualitative, quantitative or a mixture of the methods (Hoolohan et al., 2019). In some cases, quantitative scenario methods are coupled with qualitative participatory approaches, in a process that takes into account the incorporation of stakeholders' perceptivities in evaluating uncertainties from different ranges of future outcomes and developing capacity for relevant decision-making (Dixon et al., 2014). According to Heijden et al. (2002), scenarios are characterized by three key features, namely, plausibility, consistency and relevance. Plausibility emphasizes the need for scenario narratives to credible portray feasible futures, taking into account views of the changing world, including logical assumptions of such changes (Bows et al., 2012). Consistency addresses the need for scenarios to follow a reliable internal narrative, whereas relevancy is concerned with providing scenarios narratives that are adequately detailed to fully benefit from its use (Hoolohan et al., 2019).

Scenarios are commonly classified into three categories (also termed storylines, following the definition of scenarios). These scenario storylines are named exploratory, normative and business-as-usual. Exploratory scenario storylines mostly describe plausible scenarios covering long-term ranges from 20 to 100 years into the future. The development of these scenarios adopts a co-evolutionary approach where assumed development pathways give rise to different outcomes over long-term projections (Lorenzoni et al., 2000a; 2000b). The exploratory scenario approach has been applied in environmental assessment reported in the IPCC Special Report on Emissions Scenarios (Nakicenovic et al., 2000). Normative scenario storylines describe a series of events and causal relationships designed for the desired future outcomes. Normative scenarios are mostly applied in policy assessments to achieve desired outcomes over a short time frame. The business-as-usual scenario storylines are also used in short-term policy assessments to evaluate the impacts of fairly identified, near-term fluctuations in regulatory contexts, with assumptions while policy effects might dominate, broader trends will least influence the changing world over short-time projections (ESPON, 2007). The concept of scenario development is well described in business management textbooks, see, for instance, Van der Heijden (2005) and Schwartz (2012). In addition, a comprehensive overview of the practice of environmental scenario analysis is described in Alcamo (2008).

The current study considered two approaches to formulate WEF nexus scenarios while interfacing with SDGs. The first approach involves a scenario canvas (being a representation of exploratory scenario storylines) described in section 3. On the other hand, the second approach is largely quantitative and involves the application of WEF nexus empirical tools that are used to determine the linkages and trade-offs of the WEF resources with the integration of plausible futures that involve: 1) societal development options, 2) environmental changes, 3) socio-economic and political changes, and 4) technological changes. All these considerations are often embedded in climate change projections such as Representative Concentration Pathways (e.g. RCP 4.5 and 8.5), and the Share Socioeconomic Pathways (SSP2 and 5).

5.4. Scenario Canvas for WEF Nexus and SDGs' Performance

Figure 45 shows a canvas of WEF Nexus scenarios for the assessment of sustainable development goals performance. The scenarios reflect the importance of an integrated WEF nexus approach as an entry point to capture and utilize potential synergies in the implementation and achievement of SDG-2, SDG-6 and SDG-7 collectively as well as cascading to other linked SDGs. Scenario 1 focuses on a case of a high level of sustainability and high WEF resource management, scenario 2 on compromised sustainability and imbalanced WEF resource management, scenario 3 on a Low level of sustainability and imbalanced WEF resource management, while scenario 4 is on the case of low level of sustainability and balanced WEF resource management.

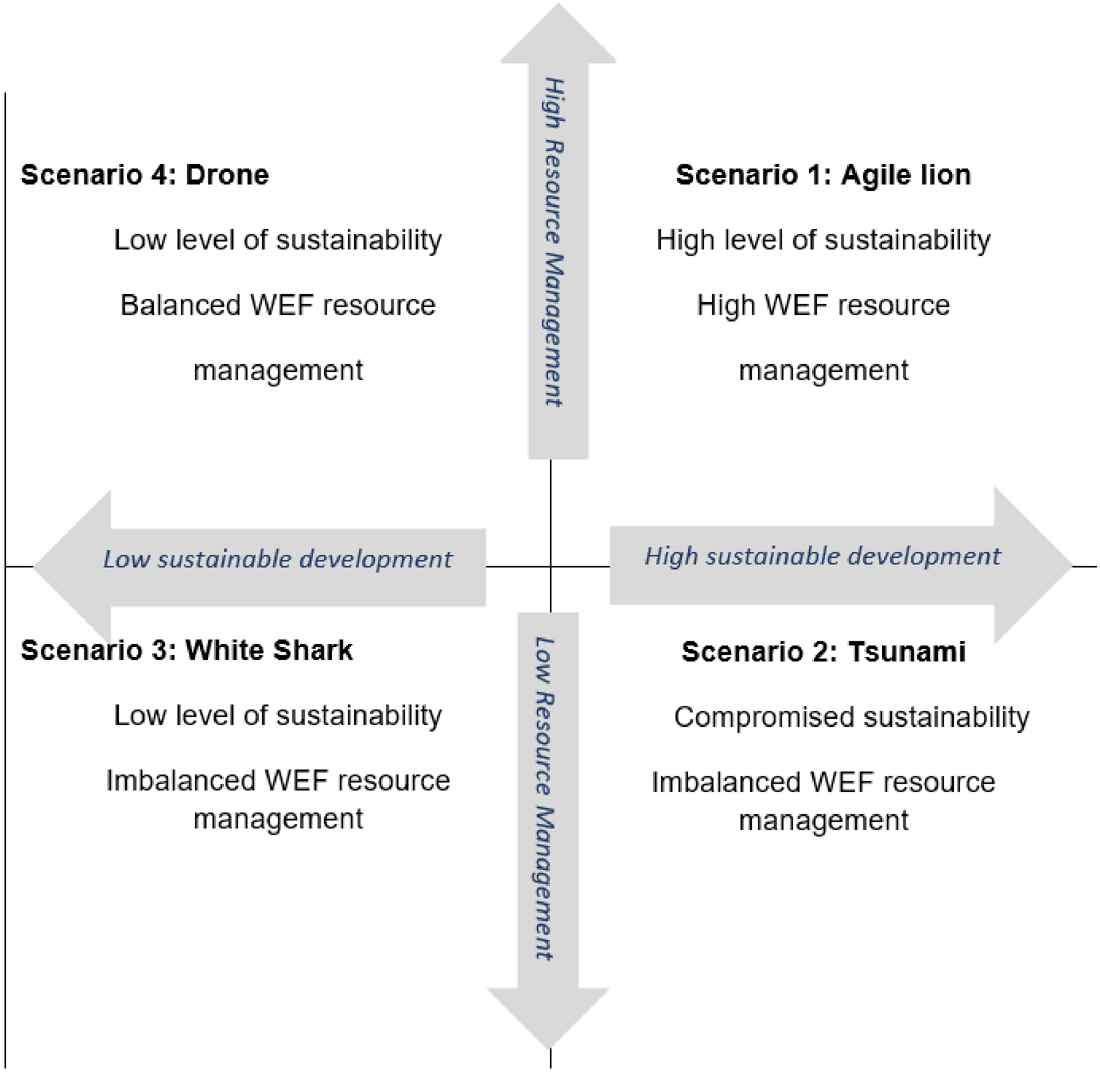

Figure 45. The canvas of WEF nexus scenarios for the assessment of sustainable development goals performance across the Limpopo River Basin (LRB) and Mara River Basin (MRB).

5.4.1 Scenario One

Scenario 1 considers a case where there is a high level of sustainability and high WEF resource management. This is a hypothetical scenario that may be very difficult to achieve. It entails a high level of efficiency in the management of the WEF resources translating to significant progress towards the achievement of WEF SDGs (SDG-2, SDG-7, and SDG-6 respectively). Noting that trade-offs are critical in the management of WEF resources in both LRB and MRB, this scenario assumes that the key to the current and future sustainable development linked to these resources include balancing supply and demand at all scale and under all environmental conditions. There is an effective and accurate understanding of the interactions between relevant policies, strategies, and economic and sustainable development in both study sites. A high level of sustainability means that there is adequate food production, high crop yields, and economic capacity to buy and maintain agricultural/farming equipment such as tractors, irrigation systems, and fertilizers. The high

WEF resource management consequently results in the achievement of the linked SDGs. For instance, assuming that the relevant policies and strategies are well supported and understood, if food security (SDG 4) is good and the communities have the required adaptive capacity and resilience to weather and climate events that might impact crop yields, SDG 1 on zero hunger would be achieved. This scenario also entails that there is significant progress towards the achievement of SDG 7 which is a key enabler in the achievement of other SDGs. McCollum et al. (2018) point out that access to energy services (e.g. lighting, and clean cooking) can greatly enhance gender equity and the quality of education. Griggs et al. (2017) argue that SDG 7 is the second most interconnected goal, with links to SDGs 1, 2, 3, 6, 8, and 13. An example of the interlinkages is improved health impacts (SDG 3) due to the reduced use of biomass for cooking and the positive impacts of using clean energy on industrial development and job creation (SDG 8). SDG 11 on sustainable cities and communities requires energy, food, welfare, and good health and many aspects of the other goals and further shows the impact that efficiently managed WEF resources have on other SDGs. When there is a high level of sustainably and efficient resource management it is expected that all environmental impacts of health-related activities such as the impact of waste from health, water and energy use, etc. are taken care of which is a big step towards meeting the SDG targets across the study sites. Additionally, the existence of good governance, well-supported policies, financial resources, resilience, and adaptive capacity with the communities or regions in both LRB and MRB could result in increased migration, population growth, and increased demand for WEF resources which will need continuous monitoring and efficient management.

5.4.2 Scenario Two

Within the context of this scenario, the management of WEF resources is unbalanced which compromises sustainability across the three pillars of sustainable development. The entrenched imbalances in the sustainable use and management of WEF resources threaten the progress and achievement of SDGs which directly relate to water, energy, and food (Malagó et al., 2021). The imbalance can be attributed to the growing scarcity of the WEF resources coupled with weather and climate impacts as well as increased socio-economic activities brought about by rapid population growth, urbanisation, shifting consumption patterns, ageing infrastructure, and competing land-use patterns that have widened the trade-offs in the WEF resources with added inequalities in their management (Mabhaudhi et al., 2021; de Vos et al., 2021). When pressured, the WEF resources become degraded, thus leaving millions of people around the world with water, energy, and food insecurity (Johnson and Karlberg, 2017). To add to this burden is the dependency of WEF sectors on the same resources or inputs and the interdependencies of resources, where the demand for one resource has driven the demand for other resources, thus resulting in a WEF trilemma, in some instances. For example, the competing water demand and supply between food production and industrial usage, which directly affects economic development, and households' consumption, and lastly, applications in utilities such as energy production (hydropower generation). As captured by Hua et al. (2021), water resources due to their application in both the food and energy sectors are coined the "hotspot issue" in WEF security. The direct impact on water resources is noted in the LRB, which is currently under stress due to current climatic conditions that are projected to worsen in the future (Zhu and Ringler, 2012). The same pressures are observed in the MRB (Zermoglio et al., 2019). Consequently, agricultural activities that characterise these two basins are compromised by drought on one hand and by water security issues on the other hand, which results in a cascading effect on the quantity and quality of food with a direct bearing on livelihoods.

While various policies for the holistic management of WEF resources exist in some parts of the world, the implementation of these policies that underpin society is still lacking, and in some regions, these policies are still in the conceptual or design stage, so there is a need for a shift from "nexus thinking to nexus doing" (Bizikova, 2019). Additionally, the balance between economic growth, and social and environmental outcomes still needs to be worked out and key opportunities and barriers identified. Such an integrated approach and consideration will bring together the science of the WEF nexus and policy implementation that will ultimately bridge the imbalance gap in WEF resource management. The participation of multi-stakeholders from both the private and public sectors will, in turn, facilitate the advancement and realisation of all SDGs.

5.4.3 Scenario Three

Scenario 3 reflects what can be seen as a business-as-usual scenario for both sites whereby there is continued mismanagement of WEF nexus resources resulting from excessive resource consumption that will compromise the ability to meet the needs of future generations. In this scenario, environmental and social issues of concern in the LRB (e.g. loss of biodiversity, water security, and land degradation) and MRB (e.g. water and energy insecurity and land-use conflicts) may be exacerbated in the future due to drivers such as population growth and urbanisation, climate change and weak governance systems. Currently, the Vhembe District Municipality has challenges with water security as about 46.85% of the household do not have a safe and reliable water supply and about 5.5% cannot afford the cost of municipal water (VDM, 2021).

Population growth and increased urbanisation have the potential to increase the demand for WEF resources in both the LRB and MRB. Climate change and weak enforcement of policies to manage efficient resource utilization of WEF resources can compromise the ability of the governance actors to meet the SDGs. The Vhembe District Municipality for example has been experiencing progressive increases in population with a projected increase of 354 393 more people by 2030 (a 28% increase from 2011), 1 632 366 people. At present households and businesses experience frequent water outages due to ageing water infrastructure, poor maintenance of water infrastructure, lack of funding to construct new water supply schemes and expansion of water mining (VDM, 2021). In this scenario, there can be an over-extraction of water resources to support economic sectors such as mining for example at the expense of municipal/domestic and agriculture sectors. Similarly, the MRB has challenges with the enforcement of environmental laws resulting in the loss of biodiversity in the Mau Forest, the decline in water from the Mau Water Tower and conflicts between pastoralists and farming communities. If this trend continues both the LRB and MRB will have low levels of sustainability as most SDG targets including SDG 1, 4, 5 and 10 decrease inequality and reduce poverty and SDG 6.4 on water efficiency will not be achieved. Constricted development actions can increase levels of social injustice by failing to incorporate the needs of the poor including equitable access to wealth, improved access to social and basic services (e.g. health, housing, and energy), and increased climate resilience and access to resources such as water and land.

5.4.4 Scenario Four

In this scenario, the WEF resource management is somehow balanced but with a low level of sustainability. There will be policies shifting over time towards national and regional security issues, with the main focus on achieving local or national water, energy, and food security goals at the expense of broader-based development (Arbor et al., 2021). The WEF resource management can be improved through the exploitation of untapped groundwater resources for irrigation and domestic uses and the untapped abundant renewable green energy sources (Mabhaudhi et al., 2019), in addition to carbon-intensive fuels like coal and unconventional oil. Increased access and availability of water, combined with energy source diversification for energy access and availability, would contribute towards achieving food security at a local level, however, with high challenges to climate change mitigation and adaptation. The projections show that the population will grow and urbanisation will also continue under this scenario by 2100 (Riahi et al., 2017). The challenges to effective climate mitigation in this scenario include a high rate of unsustainable economic development, technological advancement that is not environmentally friendly, and more reliance on carbon versus other energy sources. Factors that make it difficult for societies to adapt to climate change include high population growth, social inequalities, low investments in human capital, regionalized worldview, and institutions that are ineffective at promoting climate adaptation or mitigation.

The WEF nexus is central to sustainable development and is a mechanism for achieving the relevant sector-related SDGs (Simpson et al., 2020): SDGs 2 (zero hunger), 3 (good health and well-being), 6 (clean water and safe sanitation), 7 (affordable and clean energy) and 13 (climate action). Adopting the WEF nexus at the regional level promotes sustainable resource utilisation and inclusive economic development, thereby improving the livelihoods and well-being of people through the design and development of cross-sectoral governance structures at the regional level like climate change policies, strategies, and adaptations plans (Mabhaudhi et al., 2019). For the LRB and MRB catchments, the WEF nexus should be adopted at a regional level for improved management of transboundary WEF resources, building resilience to climate change, and poverty reduction.

Under this scenario, investments in human capital and technological development will decline. Economic development will be slow, and inequalities persist or worsen over time. Environmental policies will focus on local issues, and this will lead to a low international priority for addressing environmental concerns leading to strong environmental degradation (Riahi et al., 2017). Therefore, this scenario with the low level of sustainability due to the different challenges stated above, such as policies shifting towards local and national security issues at the expense of broader-based development will make it difficult to achieve the relevant sector-specific SDGs.

5.5. Scenario Planning from a Modelling Perspective

Scenario planning has also been incorporated into various WEF nexus modelling tools. For example, Wen et al. (2022), used Daqing, China, as a case study and designed future scenarios that explored the impacts of departmental policies on the WEF nexus resources. Additionally, Keyhanpour et al. (2021) used the Nexus Water-Food-Energy approach in a system dynamics model of sustainable water resources management and assessed the impact of socioeconomic development on the water, food, and energy resources in Khuzestan, Province in Iran. In the simulation of the water-food-energy system dynamics model, different policy perspectives were considered. Yet still, Wicaksono and Kang (2019), used the Water-Energy-Food Nexus Simulation Model (WEFSim) to calculate the supply and consumption, availability and reliability of water, energy and food resources at a national scale and averred the WEFSiM application for resource security assessments under plausible future conditions. Unfortunately, in all these system dynamic modelling frameworks, assessment of the SDG performance is not explicit. A more representative model is being considered, through another project, that will incorporate both qualitative and quantitative models that are capable of simulating the different plausible futures of resource security (see parameters in the rectangles of the causal loop diagram in Figure 46) from the perspective SDG achievement index derived from both the scenario canvas and the Delphi outcome from expert opinions.

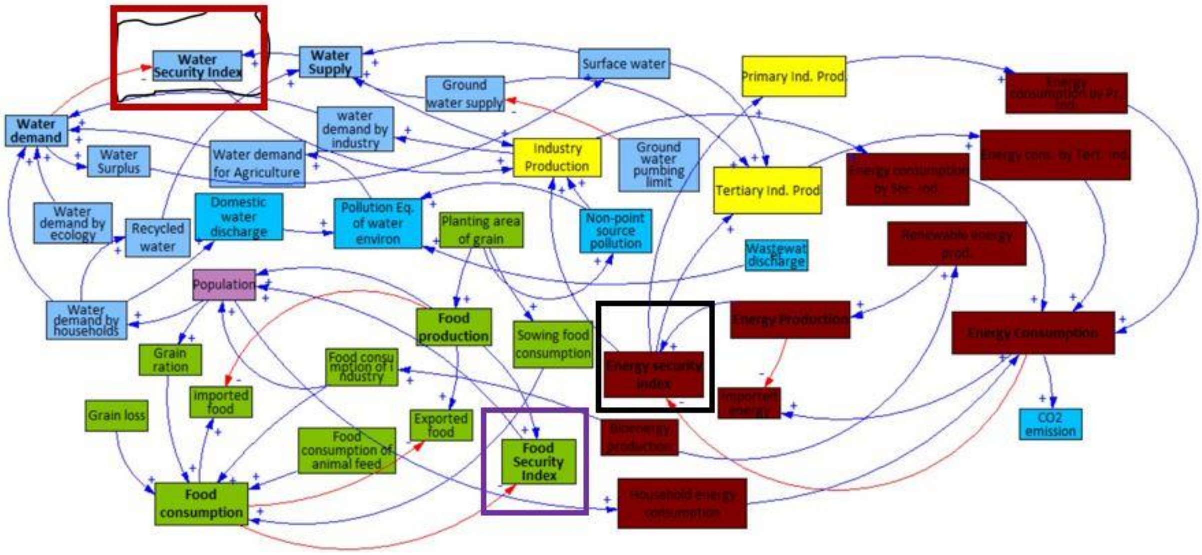

Figure 46. A causal loop diagram of the proposed scenario model for the water-energy-food nexus across the Vhembe District Municipality (South Africa) and Narok County (Kenya). Parameters in the rectangles point to the envisioned scenarios under different SDGs achievements.

5.6. Concluding Remarks

The current study aimed to conduct WEF nexus scenario planning to understand the future impacts of WEF resources and support planning and decision-making thereof, while taking Vhembe District Municipality in South Africa and Narok County, in Kenya. For this purpose, the linkages between SDGs and WEFE pillars have been determined using three case studies in South Africa. In addition, a scenario canvas has been conceptualised and used to narrate plausible futures of the study sites from the perspective of sustainability and WEF resource management under changing societal development options, environmental conditions, socioeconomic and political states, and technological advances. A more robust WEF modelling framework comprising of scenario canvas at the WEF resources security index is recommended as an ongoing future research endeavour.

6. RECOMMENDATIONS FOR IMPLEMENTATION OF THE WEF NEXUS

6.1. Introduction

Global transformational trends such as rapid population growth and changes in consumption patterns are increasing the demand for water, energy, and food. These trends strain the already overstretched natural resources, resulting in resource scarcity, and threatening the ability to support societal development and maintain necessary human rights services (Xu et al., 2022). Drivers of change and underpinning problems associated with these changes including climate change, socio-economic and political changes, impacts of extreme weather, biodiversity loss, and as well as entrenched inequalities exacerbate these stressors and will disproportionately affect the poor low- and middle-income countries in regions such as Africa. These countries, including South Africa and Kenya, currently have challenges with water, energy and food security. In the absence of an urgent switch from siloed management approaches to a cross-sectional way of thinking such as in the Water-Energy-Food (WEF) nexus concept (Liu et al., 2018), huge irreversible shifts with dire environmental and socio-economic consequences are anticipated now and, in the future, (Hoff, 2011; Flammini et al., 2014). The WEF nexus approach, emphasizes interconnections, synergies, and trade-offs between water, energy and food resources to identify solutions, promote resource use efficiency and reduce the impacts and risks of WEF nexus actions (Adom et al., 2022). It further seeks to optimize the inextricable connections between WEF resources to enhance safe, equitable and sustainable access to water, energy and food aimed at cultivating and supporting local livelihoods, while also contributing to generative livelihood outcomes.

The practical application or implementation of the WEF approach at different spatial scales (Simpson et al., 2019; Nhamo et al., 2020a, Youssfi et al., 2020) in this case at district (Vhembe Municipality) and County (Narok County) scale, will enable the two localities to meet the persistent and escalating demand for WEF resources (Chen et al., 2020). Sustainable use of these resources contributes toward attaining the United Nations' Sustainable Development Goals (SDGs), which serve as the blueprint to achieve better and more sustainable futures for all while striving to balance various goals, interests, and needs of people and the environment (Johnson and Karlberg, 2017; Norouzi and Kalantari, 2020; Naidoo et al.,2021). Although it is well understood that each of the SDGs (with emphasis on SDGs 2, 6, and 7) have been articulated as separate objectives, their achievement can be met through the WEF nexus approach which effectively aids systems thinking in interconnecting set goals and targets, therefore, creating a foundation for transformative change, necessary to address a spectrum of WEF nexus issues in the two study sites. The implementation of the WEF approach translates to the adoption of a sustainable approach that promotes innovative and integrated management of WEF resources (Norouzi and Kalantari, 2020; Adom et al., 2021). Such interventions embraced in WEF nexus case studies around the world, some of which are covered in Mohtar (2022), have been proven to support WEF nexus implementation. Practical initiatives such as integrated resource recovery, i.e. water reclamation of waste and stormwater using wetlands (Páez-Curtidor et al., 2021) are needed, which also provide ancillary benefits such as wildlife habitat function, recreational facilities, etc. (Rousseau et al., 2008). Energy efficiency, renewable energy expansion and transition to a low carbon economy all help to support nexus implementation, as well as reduce greenhouse gas emissions, among other benefits. For the agricultural sector, implementation of the WEF nexus translates to a reduction in resource inputs such as total water and energy demand (Karamian et al., 2021).

Policies, regulatory standards, and institutional responses in Vhembe District Municipality and Narok County should therefore embrace the WEF nexus approach, which takes into account the three sectors' interdependence and interlinkages. Such policy considerations have far-reaching consequences for water, energy, and food security. Other factors that contribute to WEF implementation include the involvement of various stakeholders and interest groups within communities as well as across private and public sectors (Bhaduri et al., 2015). Understanding the broader political landscape and economic analysis can identify factors that help or hinder WEF implementation. This report attempts to document the status of WEF nexus implementation and make recommendations based on the challenges observed in the two study sites.

6.2. The State of WEF Resources in Vhembe District Municipality and Narok County

Water, energy and food resources are vital for human well-being, economic development and environmental sustainability all of which contribute to the achievement of global sustainable development goals. The three resources are becoming scarce, as the demand mostly surpasses supply, particularly in developing regions of the world such as Africa (Qureshi, 2020; Biggs et al., 2015.). Climate projections, for example, indicate that the anticipated increase in climate change and frequent occurrences of natural disasters are likely to exacerbate water, energy, and food insecurities in most African countries at different spatial scales (Kusangaya., 2021; Nhemachena et al., 2020). Individuals and societies rely on energy, food, and water to survive and prosper. However, hundreds of millions of people, particularly in poor communities and rural areas, lack reliable access to these necessities in sufficient quantities and of adequate quality.

The Vhembe District Municipality is no exception, with the district having an imbalance between the supply and demand for water, alien invasion, inappropriate land uses in fragile ecosystems, pollution from mining, fertilizers and pesticides, inadequate monitoring, poorly managed sewage systems, high concentrations of pit latrines, flood events and droughts (VDM, 2022). Some households in the district rely on unclean open sources such as rivers and dams as well as groundwater resources (VDM, 2022). Communities in the district such as Masisi have reported that they are experiencing drying up groundwater sources and pollution of surface water resources (VDM, 2019). Irrigation agriculture exploits both ground and surface water resources in the basin and has impacts on other water-related sectors as well as the downstream communities of the Limpopo River Basin (Kapangaziwiri et al., 2021).

Additionally, water security and water quality in the district are threatened by the expansion of mining activities that use a large proportion of the water resulting in an additional imbalance of the WEF resources (Kapangaziwiri et al., 2021). The district thus has a relatively limited supply of both ground and surface water and is consequently stressed by the high demand for water for various activities, including agriculture, human consumption, and mining which causes disparity in the nexus components. While approximately 66% of the households in Vhembe have access to electricity, the rest of the households rely on wood since it is cheaper than other sources, suggesting the existence of diversity, and inequality in electricity access. According to Jaka (2019), the choice of fuel in Vhembe is influenced by household income, with the preferred energy sources being electricity or gas. The district has the potential to upscale other renewable energy sources such as solar and biogas from the abundant biomass available but there is a need to increase investment and awareness (VDM, 2022).

The majority of the population in Vhembe relies on rain-fed agriculture for their livelihoods (Kom et al., 2020). The agricultural system includes large-scale commercial farming and small-scale farming. According to De Cock et al. (2013) 53% of rural households in Limpopo Province are severely food insecure. Food insecurity is caused by increasing food prices, fuel and energy, political instability, economic instability, droughts, floods and environmental degradation. Developments in rural areas such as Vhembe have been constrained by the land tenure system, limited access to business opportunities, high agricultural input costs, the lack of mechanized agriculture, and disease outbreaks. The WEF resources in Vhembe are currently in a state of imbalance and require a nexus approach to meet the needs of the current and future populations. Similarly, in Narok County, the quality and quantity of water have declined due to rapid population growth, which has resulted in land-use change and cover as well as loss of biodiversity (KWTA, 2015, Richards and Syallow, 2017). The main economic activities thus include small- and large-scale farming such as livestock rearing, maize and sorghum production, tea plantations, and dairy farming. Most farmers in Narok County work without basic agricultural inputs or modernized technology and lack adequate financial and extension services to promote sustainable production (Lawrence and Rotich, 2021). In Narok County, climate change hazards such as droughts and floods are becoming more frequent, more severe, and less predictable (Korir and Ngenoh, 2019).

Many households in Narok depend on water from rivers or rainwater harvesting however these sources deplete especially in the dry months and the water is often not safe for human consumption. Additionally, population growth and land use change have resulted in the invasion of conservation areas for human settlements and increased extraction of water for irrigation in the upper Mara River which affects water availability downstream. The Ogiek indigenous people in the Mau Forest, for example, are an endangered community who practice a lot of conservation of natural resources in the forest and their livelihoods depend on beekeeping and pastoralism. Deforestation, a decline in rainfall and grazing land have left them more vulnerable and men have to travel long distances to find grazing lands while women and children are left behind. Water and food resources are therefore affected by other social economic drivers resulting in an imbalance and increased competition for land and water resources.

Energy supply in Narok is mainly from hydro-power plants, the Sondu-Miriu hydro-power plant on the Sondu River, and the catchment, in general, is estimated to have the capacity to produce 40% of Kenya's current generation capacity (Wakeford, 2017). However, forests have also been cleared for firewood as primary sources of fuel for cooking and logging. While the Energy Act (Act 1 of 2019) has been promulgated in Kenya to promote the uptake of renewable energy products and technologies and reduce deforestation, the uptake of renewable energy in Narok is low due to unaffordability for the majority of the population. The analysis of the WEF in the two study sites highlights that the demand for the WEF nexus resources is likely to significantly increase in the coming half-century due to anticipated population increase (UN, 2015); a significant increase in the global economy, with rising living standards (OECD, 2012) and urbanisation migration, leading to an increase in resource demand in urban areas (UNEP, 2013). Consequently, WEF nexus practice becomes vital for effective planning, management and reallocation of water, energy and food resources, particularly at local scales such as the Vhembe District Municipality, South Africa, and Narok County, Kenya.

6.3. WEF Nexus Implementation Challenges and Gaps in South Africa and Kenya

Globally, despite the WEF Nexus concept being well received, it has not been widely implemented and several challenges, barriers, and gaps exist in the implementation and operationalization of the WEF nexus (Aboelnga et al., 2018a, 2018b). Many researchers argue that the WEF nexus concept is still an expanding concept, without any common definitions, methods, and frameworks, and is relatively immature and narrative but not useful in applications (Purwanto et al., 2021). Liu et al. (2017) summarized the challenges for the implementation of WEF security nexus to be largely reflected by considerable data and knowledge gaps and a lack of systematic analytical tools to apply nexus thinking effectively. They highlighted that integrated modelling tools and data to quantify nexus trade-offs and synergies are still not sufficiently developed to be able to address the complexity and scales of each nexus system (Nauditt, 2018).

Currently, one of the major challenges of the WEF nexus implementation is to shift the concept from theory into practice. However, the complexity of the concept, especially where complicated interactions exist between the three sectors, their spatial scale, and seasonal variability (Liu et al., 2017) adds many challenges to embedding the concept in policies and projects (Aboelnga et al., 2018a). Several studies on the WEF nexus assessment noted that there is a lack of a versatile methodology to quantify the interlinkages between the three WEF Nexus sectors (Li et al., 2016), and also there is no single approach that fits all conditions and every case (Endo et al., 2017). A review study by Purwanto et al. (2021) outlined the literary criticisms of the WEF nexus concept which are largely centred on the apparent lack of focus in nexus studies, the lack of integration of some sectors, and the lack of common approaches to studying nexus problems. Purwanto et al. (2021) highlighted the inability to consider inherent political factors, the main democratic goal of sustainability, gender aspects, and the integration of programs, policies, and institutions at the national level, among the criticisms. Criticisms on the outcomes and impacts of the WEF nexus approach include: the nexus influence on the decision-making by stakeholders is limited and does not provide its research-backed benefits; and lack of evidence from WEF nexus research that has produced an intellectual toolkit, including validated claims that showed the improvement of resource management and governance outcomes (Purwanto et al., 2021).

Furthermore, several challenges exist in the implementation of the WEF nexus involving different sectors and a transboundary context, including conflicting uses of common resources, different water-flow regulations, and questions on how to assess and address environmental impacts (UNECE, 2018). Limitations encountered in the WEF nexus assessment process include the lack of time and resources needed to make fruitful contributions by national focal points taking part in nexus assessments; and the lack of overall participation by all sectors or stakeholders (UNECE, 2018). Potential bottlenecks to implementing WEF nexus solutions include challenges in making the WEF nexus move from externally facilitated activities towards a self-sustaining process within the concerned sectors and countries; lack of data for proper analysis and good decision-making; difficulties in overcoming national and sectoral interests standing in the way (UNECE, 2018). The implementation of the WEF nexus approach in African ecosystems is a big challenge and understanding the complexity of engagement of different WEF role-players is key to understanding the challenge of nexus approaches (Medinilla, 2021). The WEF nexus implementation gaps and under-implementation of integrated policies in African transboundary basins (Medinilla, 2021) include the following: *Form preceding function,* where donor support has led to a proliferation of 'best practice' governance mechanisms which do not always easily translate into a change in the actual practice of resource management; *Side projects,* where transformative and aspirational policies are reduced to specific, donor-funded projects while lacking a clear direct impact on the actual dynamics and governance systems they seek to reform; and *Donor signalling,* where externally driven policy integration is a commitment to policy implementation on paper, but no real changes in inter-sectoral dynamics or international cooperation is taking place.

The applicability and operationalization of the WEF nexus approach worldwide are very low, despite the recognition of the WEF nexus concept and incorporation into policy and legislative instruments in many countries worldwide (Mabhaudhi et al. 2018; Nhamo et al. 2020a). Adom et al. (2022) stated that South Africa reflects the global trend of confusion and lack of policy direction in the principle and implementation of the WEF ecosystem. Despite recognizing the WEF nexus approach, South African institutions in charge of the WEF sectors continue to operate as separate and autonomous departments empowered by the constitution (Mabhaudhi et al., 2018). The current policy environment does not promote cross-sectoral linkages and generally encourages a silos policy formulation and implementation approach (Nhamo et al. (2018). Furthermore, Mabhaudhi et al. (2018) pointed out some of the challenges facing the implementation of the WEF nexus in South Africa which include: poor education, urbanisation, and poverty; 'Silo' approach; cultural and political issues; unbalanced distribution of natural resources; climate change and variability; data availability and accessibility; and lack of funding. Adom et al. (2022) identified several structural and systematic challenges hindering the effective implementation of the WEF nexus from achieving sustainable livelihoods in South Africa. Their findings suggest that the implementation of WEF nexus policies in South Africa is hindered by a lack of qualified and experienced personnel, lack of funding, lack of political will to implement the policies, poor communication and a general lack of understanding of the nexus concept and many other constraints.

The challenges or drivers affecting the implementation of the WEF security nexus in Kenya include population growth, urbanisation, economic trend, infrastructure, unemployment, climate change, and geopolitical issues related to transboundary river basins (Wakeford, 2017). Water management, for example, has been decentralised and is managed by Water Resources Users Associations (WRUAs) that ideally promote community participation in integrated water resources management (Kenya Water Act of 2002). These community-based organisations are tasked with ensuring efficient and sustainable use of water resources, managing and reducing water use conflicts, conservation of the catchment to ensure water quality and quantity are not compromised as well as protecting the aquatic ecosystems. WRUA's have however faced challenges such as the limited authority to enforce laws and monitor environmental flows, lack of funding, transparency and agency at the local level impacting water and linked sectors (Richards and Syallow, 2018). Furthermore, outcomes of the WEF nexus operationalisation in Kenya are linked to sustainable development goals, which sounds good theoretically, however, executing it through integrated planning across the country is nonexistent (Adom et al., 2022). Likewise, there is a lack of cross-sectoral coordination among various sectors, with the fragmented implementation of projects (Weitz et al., 2017). A study on the interlinkages between WEF nexus governance and security in north-western Kenya showed that a state-centric, unidimensional security conceptualisation hinders collaborative governance, impeding stakeholder involvement and disregarding the critical significance of effective nexus governance for human security (Asaka, 2019). Like the rest of the continent, a range of institutional issues constrains the mainstreaming or achievement of trade-offs, compromises, or synergies as a means of resolving competition between the WEF sectors in Kenya (Riddell, 2015). These issues include institutional and policy silos; national and development partner institutional arrangements that do not favour integrated thinking; limited technical capacity, especially concerning lateral thinking; slow institutional evolution; rigid development plans and associated milestones that are unable to adapt to new policy frameworks; and power relationships (between national institutions and transboundary interests) that are unlikely to be softened in the short to medium term (Riddell, 2015).

6.4. Recommendations for Implementation of WEF in the selected sites

The WEF nexus approach is one of the ways that can improve the understanding of and manage the complex relationship between water, energy and food. These three sectors are some of the most climate-sensitive sectors and support the livelihoods of communities hence a nexus approach can support sustainable utilisation in the Vhembe District Municipality and Narok County. As highlighted above, both study sites currently have challenges with inequitable and unsustainable use as well as access to these resources with many community members facing food, water, and energy insecurity. The following recommendations apply to both sites and are ensued by site-specific recommendations for Vhembe District Municipality and Narok County.

1. While research on the WEF nexus is gaining momentum there is a need to ensure that key actors at the local level are capacitated to comprehend and integrate the approach at local level operations and decision-making (e.g. budget allocation in municipal planning documents and enforcement of by-laws).
2. Encourage non-state actors to get involved and provide technical as well as financial support to WEF nexus-related initiatives
3. The definitions, methods and frameworks used in the WEF nexus need to be developed further and include practical examples of where the WEF tool is applied such that decision and policymakers learn from practice rather than just theory. The methods and frameworks need to encompass both quantitative and qualitative information at multiple scales including aspects such as gender, policy development and adoption among others.
4. The Narok County and Vhembe District Municipality include transboundary water (Limpopo River Basin and Mara River Basin) and biodiversity (Kruger Trans Frontier Park and Maasai Mara National Reserve) which require integrated and coordinated efforts from governance actors to ensure the current and future needs of all communities in the upstream and downstream basin are met. National and regional legislation and agreements signed to manage transboundary policies developed need to be implemented and enforced by all actors to ensure tangible change is realized.
5. Funding needs to be channelled towards activities supporting WEF security as these can help curb poverty and unemployment in both Narok County and Vhembe District Municipality

6. The unavailability of data is a challenge when implementing the WEF tools hence relevant government departments, research and academic institutions should collate data and make it accessible for analysis of the interaction between WEF resources, scenario planning and decision making in local contexts.

6.4.1. Recommendations for Narok County, Kenya

1. The Water Resources Users Associations in Kenya (and Mara Basin specifically) need to scale up ecosystem management activities by building the agency and capacity of local actors to effectively manage the multiple ecosystem services derived from the basin.
2. The national water governance actors in Kenya need to support WRUAs to register their associations and with the Attorney General as well as facilitate partnerships with the Water Resources Authority for them to comply with the provisions of Kenya's Water Act (2002) (section 15) and Water Act 2016 on community-based water resources.
3. Environmental laws and penalties need to be reinforced to manage illegal sand mining and deforestation for charcoal in Narok which is affecting the quality and quantity of water in rivers, causing water use conflict in local communities and a decline in forests and biodiversity.
4. Local communities, academic and research institutions should work together with governance actors to support the implementation of national policies such as the Energy Act by providing local county-level data and making renewable energy alternatives more affordable
5. Integrate local knowledge and priorities in natural resource management to ensure both short and long-term needs are met. WRUAs need to be more active in designing local water management initiatives.
6. Procedures to address water and environmental non-compliance should be transparent to enable greater accountability and uptake of policies and initiatives at the community level

6.4.2. Recommendations for Vhembe District Municipality, South Africa

1. Research and academic institutions should proactively provide capacity-building, useable and relevant information (such as simulation of dam operations on the downstream communities as well as how to optimise different uses of existing water resources) that supports local integration of the WEF nexus concept.
2. National government departments such as the Department of Forestry, Fisheries and Environment, the Department of Water and Sanitation and the Department of Agriculture, Land Reform and Rural Development should provide support and facilitate access to technical and financial support for rural communities in the basin to be proactive in protecting the WEF resources from current and future impacts of climate change and variability, population growth, land use change among other drivers.

3. Promote sharing of indigenous knowledge to support early warning and disaster response and agricultural activities such as the growing of drought-resistant crops and preservation of grains to reduce vulnerability
4. Enforce national policies to manage water pollution from economic activities such as mining and agriculture to reduce the eutrophication of water bodies.
5. Diversify income and livelihood activities to improve food security and resilience to global and climate change
6. Promote uptake of renewable energy products and technologies to reduce deforestation and use of other fossil fuels

6.5. Concluding Remarks

Climate change, coupled with other social, economic and environmental factors is likely to affect the supply of water, energy and food resources at different spatial scales. The proposed WEF nexus approach is ideal for understanding the interlinkages between the WEF resources and can be used for better management and planning of these resources. The current study proposes recommendations for the implementation of the WEF nexus approach in Vhembe District Municipality and Narok County. The proposed recommendations considered existing WEF nexus vulnerabilities within the studies. In addition, possible challenges that can impend the implementation of WEF nexus practice in both sites have been highlighted.

7. RESEARCH AGENDA FOR FUNDING RESEARCH AND DEVELOPMENT ON WEF NEXUS

7.1. Introduction

The water-food-energy (WEF) project focused on various aspects that were reported in the deliverables that constituted the chapters in this report. These deliverables include the literature review that focused on the assessment of the WEF nexus in southern and eastern Africa, identifying status, opportunities, and regional case studies for the WEF nexus. The following activity applied the integrated Water-Energy-Food (iWEF) nexus analytical model to evaluate interlinkages among variables in the WEF system in Vhembe District Municipality, South Africa, and Narok County in Kenya. This provided an understanding of the WEF nexus and the associated trade-offs that are required to facilitate the allocation and management of WEF resources in an integrated and sustainable manner in the two study sites to support decision-making including effective use, allocation, and management of the WEF resources at the local level. The project also assessed the livelihoods, human health and well-being in the two study sites. To support monitoring and evaluation, and sustainable use of the nexus resources to achieve global and national SDGs, the project selected indicators from various WEF nexus studies (Pahl-Wostl, 2019; Abubakar, 2021; Wolde et al., 2022) which were adopted to assess the interactions between the nexus aspects and their impact on livelihoods, human health and wellbeing in the two study sites.

Following this, a framework for WEF nexus scenario planning was developed to support decision-making on water, energy and food economic sectors in the study sites. This was achieved by reviewing the literature on linkages between SDGs and WEFE and testing the interconnections between WEFE pillars and SDGs in the study sites. The study went further and documented the status of WEF nexus implementation and made recommendations based on the challenges observed in the two study sites. This revealed the importance of policies, regulatory standards, and institutional responses that embrace the WEF nexus approach, taking into account the three sectors' interdependence and interlinkages in the study sites. The findings of this project have informed this chapter and seek to develop a research agenda for funding future research and further development of the water-energy-food nexus.

7.2. Current and Future Research Priority Areas

The findings of this project suggest that the WEF nexus approach can contribute to sustainable management and development of the WEF nexus sectors whilst increasing awareness and building capacity for integrated planning of investments and identifying and evaluating trade-offs and synergies. While some work has been done to date on the WEF nexus there are still gaps in knowledge that can be addressed through future research and the proposed areas that should be funded include:

Addressing data and knowledge gaps

Factors such as globalization, urbanisation, industrialization, and climate and environmental change continue to add pressure on water, energy and food security in African countries such as Kenya and South Africa (Lawford, 2019). Consequently, food production capabilities as well as water and energy accessibility and availability are often unevenly distributed across the continent. Based on the gaps identified in this project, sector-specific data, tools and knowledge generation thereof are essential for the effective implementation of the WEF nexus approach and resource sustainability (e.g. better management, planning and decision-making). Proposed research areas to support data collection, analysis, knowledge generation and information dissemination include:

- Assessment of the WEF nexus data availability at different spatial and temporal scales, and collation of existing data and knowledge gaps
- Developing integrated WEF modelling approaches that are based on physical and social data as well as metrics

Promote WEF nexus implementation using multi-disciplinary approaches

The WEF nexus concept captures the interdependence, synergies, and trade-offs between the demand for water, energy, and food in the context of increasing sustainable development restrictions (Scott et al., 2015). To meet these growing demands and to advance the attainment of SDGs, there is a need to transition from silo-thinking to a multidisciplinary (and transdisciplinary) approach to address the challenges of the nexus applicability in the real world-thus move from theory to practice (Ghodsvali et al., 2019). Examples of research topics that require multidisciplinary approaches to address the interrelated WEF challenges in a more coordinated and sustainable manner include work to evaluate the synergies and trade-offs of the WEF nexus using multi-disciplinary approaches and analysis of different WEF stakeholders' needs through integrated multi-disciplinary approaches.

Support integrated governance and policy implementation for effective management of WEF resources

Relatively little consideration has been given to the governance of the WEF nexus resources, and the significance of spatial and temporal scales has been largely disregarded (Pahl-Wostl et al., 2020). This gap has resulted in several limitations that have affected the implementation of the WEF nexus in support of livelihood across the broad socio-economic spectrum. As captured in Lazaro et al. (2021), Better integration of scientific understanding and policy-making will be achieved by determining the most effective means of integrating the development of policies and governance, as well as stakeholder actions to support cost-effective decisions for optimal resource management and regulatory procedures(Lazaro et al., 2021). Summarised below are some of the priority research areas related to the governance and management of WEF resources that should be considered.

- Integration of national institutional and transboundary policies and governance for WEF nexus operationalization
- Development of an operational framework to drive and guide sectoral collaboration in implementing priority WEF investment projects
- Public-private partnerships for WEF nexus implementation and operationalization
- Maximising the development impacts to improve sustainable financing of nexus projects and attract financing from various sources including investment finance from commercial funders, private investors and grants from donor organisations
- Development of efficient infrastructure, technologies and practices through coherent policies and good governance
- Analyse the impacts of United Nations Climate Change Conference (COP) agreements (Climate change pledges and action) on the WEF sectors and WEF nexus tools for enhanced climate resilience

Improving understanding of the impact of the global pandemic on the WEF nexus

The recent outbreak of the Coronavirus disease (COVID-19) globally has provided overwhelming evidence that global pandemics can be a threat to water, energy and food resources. In addition, it has exposed several gaps in the WEF nexus debates, such as a lack of risk-based perspectives and a need for improved spatial considerations in resource integration (Al-Saidi and Hussein, 2021). For instance, during the COVID-19 era, most countries, including South Africa and Kenya, implemented large-scale human activity restrictions and strict preventative lockdown measures to prevent disease spread. Retail and education are some of the sectors impacted by the pandemic. Additionally, electricity consumption increased due to lockdown measures that required most people to work remotely from home and schools' online learning. Consequently, most countries experienced challenges related to challenges to electricity planning at the generation, transmission, and distribution levels. To mitigate such impacts, there is a need to conduct assessment studies to understand the impacts of global pandemics such as COVID-19 on the WEF nexus and related risks that may hamper its implementation. Research areas within the global pandemic may include:

- Assessing the short- and long-term impacts of the COVID-19 pandemic on the WEF sectors and the interlinkages of the impacts on other linked sectors in the socioecological system
- Characterising the impacts of recent pandemics and modelling the impacts of future pandemics on the WEF nexus

Examining the impacts of geopolitical dynamics on the WEF nexus implementation

Geopolitical challenges often cut across areas such as natural resources, trade, armed conflict and climate change. Such dynamics have impacts on WEF resources which have varying impacts on the components of the nexus. For instance, the recent armed conflicts between Russia and Ukraine have hindered international efforts to eradicate hunger, including the achievement of Sustainable Development Goal 2. Most countries, including the UK and South Africa, have been affected by the Russia-Ukraine war, where food and energy supply disruptions resulted in excessive prices of imported food items as well as gas for cooking and heating. Undoubtedly, the food security debate needs to consider the impacts of geopolitics (i.e. an important dimension of political failure) across various areas that directly affect food security. These include impacts of the Organization of the Petroleum Exporting Countries (OPEC) Plus oil price and supply agreements on the WEF nexus as well as impacts on global energy markets, global food security, and the fight against climate change.

7.3. Conclusion

The comparative study between Kenya and South Africa has highlighted some of the challenges in implementing the WEF nexus at the catchment level as well as the gaps in knowledge. The recommendations for future research and interventions for the WEF implementation at the subnational level include facilitating mechanisms to promote private sector funding for WEF research and projects at the subnational level. The research has also highlighted that there is a need to create an enabling research-policy-practice environment to ensure the uptake of science recommendations to support sustainable utilisation and management of nexus resources particularly given the emergent risks associated with pandemics and global change. Furthermore, there is a need for more research studies that adopt the county level (Kenya) or district development model (South Africa) to enhance community involvement in such studies in co-designing socially inclusive actions to sustain the WEF and linked resources in rural, semi-urban and urban contexts. Future work can also document and advertise practical cases of successful outcomes of the use of the WEF Nexus approach but the multiscale data that feeds into the WEF nexus modelling is often difficult to access, hence platforms should be created to allow for easy access to this data. Lastly, transdisciplinary studies are required to draw on stakeholder perceptions of the WEF nexus and its priorities. Feedback from these engagements will be used to among other things develop guidelines for best practices for partnerships that are present or should be created to improve the local livelihoods, environment, and human wellbeing.

8. OVERALL CONCLUSION AND RECOMMENDATIONS FOR FUTURE PROJECT IMPLEMENTATION

8.1. Overall Conclusions

Climate change and population growth, coupled with other socio-economic and environmental challenges such as rapid urbanisation and land degradation are likely to have an impact on the supply of water, energy and food resources which will affect the livelihoods of vulnerable communities, especially in Sub-Saharan Africa. The WEF nexus approach is one of the ways that can improve the understanding of and manage the complex relationship between water, energy and food. Currently, one of the major challenges of the WEF nexus implementation is to shift the concept from theory into practice and some other challenges have hampered its implementation at different spatial and temporal scales. Such challenges are attributed to existing knowledge gaps in understanding WEF resources interlinkages, limited availability of reliable tools and models, the lack of the necessary data to develop and test such technologies as well as the overall value-chain translation of the WEF nexus concept from theory to practice. This project contributes towards building and enhancing WEF nexus body knowledge in support of the implementation of the nexus approach for effective management of WEF systems at a local scale, using case studies in Vhembe District Municipality, South Africa, and Narok County in Kenya.

This project aimed to develop a robust nexus modelling methodology that will be realised in the form of a smart decision tool that is applicable and cognisant of the cross-sectoral complexities of the WEF resources in Eastern and Southern Africa in a changing climate. The bibliometric analysis conducted in this project examined the current trends, opportunities and gaps in water, energy and food nexus research in Africa, with a particular focus on the eastern and southern African regions. The literature highlighted that in Africa, six main WEF themes have been the foci of research and examined WEF linkages to water resources, water supply, resource management, decision making and climate change. Although significant research is being conducted in Africa, there are three key emerging themes that the WEF nexus research should pursue in Southern and Eastern Africa. Firstly, there is a need for further research to explore how the WEF nexus can support the transition towards sustainable development pathways as well as influence policy to address some of the key developmental challenges in Africa such as poverty, water scarcity, and food and energy insecurity. Secondly, there is a need to improve understanding of how the WEF nexus can support food production and supply including strengthening the capacity of smallholder farmers to increase productivity and resilience to shocks and stressors such as climate variability and economic instability. The last emerging theme that needs to be interrogated further in Eastern and Southern Africa is water management, particularly given the increasing competition for water and the projections of increased temperatures and drying in parts of these two regions which will result in increased demand for the scarce resource.

In addition, the literature review has identified several issues that constrain the mainstreaming or achievement of trade-offs, compromises, or synergies in the resolution of the competition between the nexus elements. The key nexus issues for southern Africa include cross-sectoral policy linkages among WEF sectors, the impact of climate change on WEF resources, at local and regional levels, irrigated agriculture from the WEF perspective, coordinated action through sector policies and cross-sectoral linkages, analysis of interlinkages between charcoal, livestock, and hydrological processes. Furthermore, there is a need to develop climate change adaptation strategies within and across the region, which include: promoting climate-smart agriculture, developing early warning systems, and integrated water resource management. Additional response actions include adopting renewable energy options with a low carbon footprint, as well as increasing monitoring and modelling capacities across each of the nexus components, and promoting the implementation of coordinated actions through transboundary and national sector policies and cross-sectoral linkages.

The interlinkages among variables relating to water-energy-food resources in the two sites were evaluated using the iWEF nexus analytical model and the built-in WEF nexus indicators in the model were assessed based on a desktop analytic study and survey questionnaire. The integrated composite indices for Vhembe and Narok suggest that resource management is marginally sustainable in both river basins. Furthermore, the results showed evidence of imbalanced resource management across the river basins and the outcomes of the assessments can help inform policy interventions related to the assessment and test the performances of the indicators against the relevant policies for both Kenya and South Africa. The study also identified indicators that highlight the interactions between the WEF nexus components and their impact on livelihoods, health and well-being from literature and based on the stakeholder survey that was carried out in Narok County. The results showed that the WEF components play a critical role in the improvement of people's livelihoods, health, and well-being. Furthermore, factors such as population growth as well as rapid and unplanned urbanisation were identified as having a huge impact on the nexus components and consequently also affecting the livelihoods, health and wellbeing of the communities in both Vhembe and Narok. Transect walks within the study sites highlighted the impact of these two key factors as evidenced by the decline in forests as land has been changed to human settlements, land degradation, pollution of rivers and deforestation. Discussions with participants in Narok also highlighted that the county is highly vulnerable to climate change and some notable changes observed include an increase in intense storms that cause flooding, droughts, an increase in pests and diseases affecting crops and changes in the onset of the rainfall season. The project also included WEF nexus scenario planning to understand the future impacts of WEF resources and support planning and decision-making in the study sites. A scenario canvas was conceptualised and used to narrate plausible futures of the study sites from the perspective of sustainability and WEF resource management under changing socioeconomic and political states, environmental conditions, and technological advances.

8.2. Overall Project Recommendations

Based on the literature analysis, there is a need for nexus research to influence policies and coordinated governance of water resources in transboundary basins to ensure their sustainability. There is also a need to address issues identified in literature such as institutional and policy silos; national and development partner institutional arrangements that do not favour systems thinking; limited technical capacity; rigid development plans as well as dynamic power relationships between national institutions and transboundary actors who may have different interests. This can be achieved through coordinated regional efforts that consider the comparative productive advantage of investments across the nexus value chains to expand and diversify livelihoods. The outcomes of the iWEF model illustrated that resources are not managed sustainably within the two regions, hence it is recommended that both study sites consider more efficient and integrated ways of allocating resources to improve other indicators without compromising food security and water availability productivity. Furthermore, the results of this work provide evidence in support of the recommendations reported in Aboelnga et al. (2018b) that there is a need to support integrated transboundary management of the basin and to design policies to holistically attain these development objectives through efficient use of resources. Additionally, it is recommended that similar assessments of cross-sectoral interactions need to be done in Africa to improve understanding and inform policies The findings of the scenario planning done in this study highlighted the need for a more robust WEF nexus modelling framework comprising of scenario canvas of the WEF resources security index.

Overall, for both sites, it is recommended that key actors at the local level are capacitated to comprehend and integrate the nexus approach at local level operations and decision-making (e.g. budget allocation in municipal planning documents and enforcement of by-laws). Narok County and the Vhembe District Municipality include transboundary water which requires integrated and coordinated efforts from governance actors to ensure the current and future needs of all communities in the upstream and downstream basin are met. National and regional legislation and agreements signed to manage transboundary policies developed need to be implemented and enforced by all actors to ensure tangible change is realized. Non-state actors should also be encouraged to get involved and provide technical as well as financial support to WEF nexus-related initiatives. In addition, the definitions, methods and frameworks used in the WEF nexus need to be developed further and include practical examples of where the WEF tool is applied such that decision and policymakers learn from practice rather than just theory. The methods and frameworks need to encompass both quantitative and qualitative information at multiple scales including aspects such as gender, policy development and adoption among others. There is also a need for funding needs to be channelled towards activities supporting WEF security as these can help curb poverty and unemployment in both sites. Data availability was one of the challenges encountered during the execution of this project. Based on this challenge, it is further recommended that relevant government departments, research and academic institutions collate data and make it accessible for analysis of the interaction between WEF resources, scenario planning and decision-making at various scales.

In terms of the research agenda, the following recommendations are some of the future research and interventions for the WEF implementation at the subnational level that were put forward: facilitate mechanisms that promote private sector funding for WEF research and projects at the subnational level; create an enabling research-policy-practice environment to ensure the uptake of science recommendations to support sustainable utilisation and management of nexus resources particularly given the emergent risks associated with pandemics, political unrest and global change; research studies can adopt the county level (Kenya) or district development model (South Africa) to enhance community involvement in co-designing socially inclusive actions to sustain the WEF and linked resources in different contexts; In conclusion the study has highlighted that the WEF nexus approach has potential to support sustainable management and utilisation of resources in Africa however, there is need for more transdisciplinary studies to support decision makers at various scales based on evidence.

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APPENDIX 1

Appendix 1.1. A synopsis of WEF nexus published articles in Africa

Reference	Country/region	Aim/objectives	Main theoretical framework/type of WEF nexus being considered	Policy implications/applications	Research gaps or recommendations
Gulati et al. (2013)	South Africa	Interrogates how energy and water costs influence the price of food. Test hypothesis of whether energy inflation is the primary cause of food inflation and identify any other factors at work	Green economy developmental mode; Integrated resource management approach; WEF nexus	Environmental and human security for shared water, energy resources and its impacts on food security; Inform policy and on infrastructure for improved, cost-effective agricultural production and processing; Investment in research and development to improve production efficiencies and rechanneling social grants to food banks and work for food programmes	Gaps in knowledge on the complex dynamics and dependencies of water, energy and food pricing Need further studies to provide a more detailed understanding of the production cycle, food prices and food security linkages. How to address the trade-offs in the nexus to effectively address food security
Hanjra et al. (2013)	Africa and Asia	Identify interventions and policies for tackling food security: agriculture for development, ecosystem services from agriculture, and gender mainstreaming, to extend the focus on food security within and beyond the agriculture sector, by incorporating cross-cutting issues such as energy security, resource reuse and recovery, social	Climate change challenges in terms of increased variability and risk for food producers and the energy and water sectors – WEF	Global food security; governance models and regional priority setting wrt. food security; gender mainstreaming	Need to look beyond agriculture and invest in affordable and suitable farm technologies to address the food insecurity problem in a sustainable manner

		protection programs, and involving civil society in food policy-making processes by promoting food sovereignty.			
Keulertz and Woertz (2015)	Egypt, Morocco, Tunisia, Lebanon, Algeria, Sudan and Jordan	The article explores five different pathways of how Arab countries could finance green growth projects ranging from regional financial markets to concessionary loans by funds from oil-rich Gulf countries.	Green growth and neoliberalism	WEF nexus is often conceptualised as a technical term yet there are political and financial dimensions that can affect its implementation. Financial reforms are required to fund hydrological externalities as public goods especially in countries with limited water endowments permits	
Jobbins et al. (2015)	Morocco	Assess the water-energy-food nexus concept from a bottom-up perspective using three cases studies of drip irrigation adoption by small scale farmers in Morocco	Water energy and food nexus	Does not reduce overall consumption and adoption Policies supporting water and energy efficiency can also have unintended outcomes such as worsening poverty and inequality	WEF nexus concept may offer useful insights, its use in policy formulation should be applied with caution. There is a need to provide context-specific best practices to reduce the impacts of WEF on poverty and inequality.
Conway et al. (2015)	Southern Africa	The aim was to examine southern Africa's nexus from the perspective of climate and modify Hoff's nexus framework11, which integrates global trends (drivers) with fields of action, to highlight the role of	Based on Hoff's nexus framework11. Authors consider the main elements of intraregional links in water-energy-food at a national level while	Supports policies on water, food and energy security, climate change within the region. Highlights main interdependencies and key regional institutional and policy structures in southern Africa	Use of a nexus framing to identify approaches and methods for cross-sectoral integration by examining trade-offs and co-benefits, and improvement of governance. Vertically structured

		climate as a driver and anthropogenic climate change. – Consider national-level exposure of water, energy and food production to climate variability in aggregate economic terms and analyse the relationship between inter-annual and multiyear climate variability and economic activity, focusing on GDP and agricultural production. – Outline the potential for seasonal climate forecasting in areas with high forecasting skill and socially and economically important nexus related activities, – describe three key intraregional mechanisms for balancing nexus components, – Identify knowledge gaps in southern Africa's climate and water-energy-food nexus.	highlighting connections on the river basin scale and drawing attention to case studies of examples of trade-offs and synergies.	pointing to regional strategy and policy formulation to better achieve cross-sectoral coordination. Points to strong nexus interdependencies due to multiple shared major river basins and aquifers, the SAPP power-sharing infrastructure, and intraregional food and embedded water trade enhanced by governance mechanisms such as the SADC, which has established protocols on shared water, energy and food security, the Southern Africa Regional Climate Outlook Forum, and initiatives on trade and the green economy.	government departments and sector-based structures of agencies, policies and regulatory mechanisms complicate coordination, remain challenges to cross-sectoral integration. The political economy of governance and operation is also challenged by regional and intraregional institutional capacity and power imbalances. Climate change and increasing demand associated with wider socioeconomic development pathways will intensify interdependencies in the water-energy-food nexus, particularly shorter-term pressures associated with extreme events.
King and Jaafar (2015)	The Middle East and North Africa	Qualitatively analysis of effects of rural households' green water management practices on basin-level water, energy, food and carbon stocks and flows are in six basin agro-ecosystems.	Exploration of trade-offs under critical transitions affecting agricultural water use	Support policies on water conservation and management	Increased strategic support for green agricultural water management practices appears stronger when weighed from the nexus perspective, rather than purely

					from water balance and food production.
Ozturk and Ilhan (2015)	BRICS Nations Brazil, Russia, India, China and South Africa	To explore the different ecological indicators which are relevant to long-term sustainability within the water-energy-food (WEF) nexus among BRICS nations.	A food security index was constructed using principal component analysis comprising of agricultural value-added, land under cereal productions and agricultural machinery.	The study makes note that policymakers globally are challenged to devise flexible water management policies. Reduce the environmental footprint can be achieved by investments to boost water productivity and to improve energy use efficiency in crop production.	There are significant findings in this study that motivates new and better integrated economic-environmental policies across the BRICS nations.
Amos et al. (2016)	Kenya	The study aims to examine the economic aspects of domestic rainwater harvesting (RWH) in urban and peri-urban environments.	Socioeconomic benefit analysis of rainwater harvesting in the WEF NEXUS	Support policies on water conservation and efficient resource use to improve understanding of the full benefits of RWH (return on investment)	Results are on financial benefit studies have produced conflicting results. There is a need for further research studies on economic analyses have ignored the full benefits that a RWH system can offer and standardize the methods of economic analysis of RWH systems.
Pieters and Swinnen (2016)	Saudi Arabia	WEF nexus framework is used to analyse the interplay of water scarcity, relative energy abundance, and food production and consumption in the Kingdom of Saudi Arabia	WEF nexus	Major reforms to reduce the use of highly subsidized but very scarce water for domestic feed and food production. Developing strategies to meet the KSA food security objectives	Recommendations to develop an extensive food security strategy in which food stocks and subsidies are complemented by in-kind and cash transfers

				Policy transformations and revisions regarding forage crops to save scarce water resources.	
Gleeson et al. (2016)	Africa – nonspecific	This paper is an evaluation of the topics presented by mountain researchers at the Future Earth conference. Based on the findings, the paper outlines a proposal for the future directions of mountain research.	Conservation of natural resources to support ecosystem health and adaptive governance through the WEF nexus		Opportunities for partnerships for further mountain research in relation to Water-Energy-Food Nexus to address cross-cutting societal issues
Ozturk (2017)	Sub-Saharan Africa	To examine the dynamic nexus between water-energy-food (FAW) poverty and agricultural sustainability throughout selected countries in the sub-Saharan Africa region.	The study used pooled fixed effects, pooled random effects and pooled least squares regression techniques to absorb country-specific-time-variant shocks.	Cereal yields, forest area and agricultural value-added decreases the WEF poverty nexus which can lead to higher economic growth and price levels but at the cost of environmental degradation.	The study makes special mention to agricultural sustainability as a prerequisite to reducing WEF poverty and should be focused on in countries which struggle with WEF poverty.
Endo et al. (2017)	Asia, Europe, Oceania, North America, South America, Middle East and Africa	The purpose of this study was to review and analyse the water, energy and food nexus under the study region, nexus keywords and stakeholders to understand the current state of nexus research.	Bibliometric analysis approach using secondary data included in publicly available academic publications in journals and on the web.	Develop methods such as integrated indices, models and economic assessment methods to integrate interdisciplinary, multi-sectors and dimensional research and trade-offs among the three resources.	Develop a unifying framework of nexus research that can be used in interdisciplinary and trans-disciplinary approaches under the future earth framework and to encourage local-global connected nexus system.
Phiri et al. (2017)	Southern Africa	The book aims to provide a thorough review of water and sustainable development of Zambezi, to identify critical issues	A review looking at the availability and use of water resources in the basin. Highlight key concerns related to	The policy implication that the book noted included utilization of hydropower and the WEF nexus, sustainable agricultural water management as well as	The book recommended collaboration with government decision-makers, private sector investors, universities, WEF sectors, intermediary

		and propose constructive ways forward.	climate vulnerability and risk, the impact of urbanisation and water quality as well as ways to enhance transboundary water cooperation.	challenges and opportunities related to the provision of ecosystem services,	organisations that work directly with farmers. Lastly consider the development of hydropower generation and integration of commercial sectors such as mining.
Hoffmann et al. (2017)	Sub-Saharan Africa	The study aimed to analyse the different steps within the charcoal value chain in Sub-Saharan Africa and highlight the respective interdependencies and the potential for improving overall socio-economic and environmental sustainability.	Integrated approach linking old issues to a variety of new international developments, including the ecosystem service concept, new security approaches, the bio-economy move and the SDGs, which start to trigger a host of new national policies and funding initiatives.	The suggested 'new perspective' is argued to accommodate recent political multi-dimensional initiatives, notably the Agenda 2030.	Traditional bio-energy including charcoal does not play a role in WEF nexus and ecosystem services approach yet and there is a need for researchers and policymakers to apply them to charcoal value chains on all scales to close this gap and therewith help to solve challenges that have been present for many decades.
Zhang et al. (2017)	Africa, Asia, Europe, Latin America and North America	The study aimed to provide a systematic review of the impacts from policy, climate change and water-energy-food nexus on hydropower development at a global scale	Review on the impacts of climate change, policy and water-energy-food nexus on hydropower development	This study emphasized the importance of integrated approaches as well as cross-sectoral coordination to improve resources use efficiency and achieve sustainable hydropower development	Future research to incorporate uncertainty assessment and risk analysis associated with climate change, such as an extreme event in the development of hydropower.
Zaman et al. (2017)	Sub-Saharan Africa	This study investigated the relationship between water-energy-food production and air	The study used panel random effect model that addresses the	Short-term: sustainable food production, avoid non-organic food that is radiated by different	This study suggested the development of environmentally sustainable

		quality indicators under environmental Kuznets curve (EKC) framework in the times of financial crises, using time series data of 2000-2014 in a panel of 19 Sub-Saharan African countries.	country-specific time-invariant shocks to examine the non-linear relationship between water-energy-food resources and air pollutant.	artificial animal and crop farming. Medium-term: The Sub-Saharan African countries require a blend of renewable energy sources such as wind, solar and wave-power energy that are helpful to mitigate the concern of global climate change.	interlinked sector policies that consider global financial crises and improved energy efficiency.
Guta et al. (2017)	Asia, sub-Saharan Africa, and South America	The aim is to assess the factors that determine the successes and failures of decentralized energy solutions based on local harmonized case studies from heterogeneous contexts from Asia, sub-Saharan Africa, and South America Research questions: what are the water and food interlinkages of decentralized energy solutions; what are the incentives and barriers for the successful adoption of decentralized energy solutions under the WEF Nexus?	Energy transition and the WEF Security Nexus – the interconnectedness of decentralized energy solutions within the WEF Nexus and links the energy transitions and the WEF Nexus at the household and community levels from decentralized energy solutions perspectives	Supports Sustainable Development Goals;	Need to consider political setting, socio-cultural traditions, cooperation among multiple stakeholders, and legal rules and regulations; Policies should consider local social, institutional, economic, environmental, and technological aspects, and the skills of the households and other actors in the DES value chains, to enable the initiatives to sustain themselves without external assistance, and gradually transform themselves into self-financing businesses

Siciliano et al. (2017)	Zambia Sierra Leone Mozambique Liberia Guinea Benin Burkina Faso	The aim is to inform European policies and regulations for the development of best practices on the presence of European land investments in the global South and their implications with respect to the land water-energy-food nexus. The main objective of the study is to identify general patterns and processes useful to support the current policy debates on the potential negative implications of European farmland investments on natural resources (i.e. land and water) and their accessibility by the local population in the recipient countries	Interrogates the land-water-energy-food nexus in relation to large-scale farmland investments Land matrix to collect data on land deals that entail (i) a transfer of user rights from smallholders or collective uses to commercial uses; (ii) cover an area greater than 200 hectares; (iii) refer to land agreements announced or concluded since 2000; (iv) refer to sale, lease or concessions	Inform policy on bilateral and multilateral agreements on foreign farming investments to minimize the negative impacts on recipient countries to protect land use and water rights of local farmers and mitigate food insecurity; FAO Voluntary Guidelines on the Responsible Governance of Tenure provides a code of conduct which is voluntary and cannot be enforced. The EU, therefore, needs to implement enforceable policies that ensure that European corporations and other financial actors based in Europe operate overseas consistently with EU commitments to human rights, development and climate change	The use of information from global dataset combined with site-specific evaluation of water acquisitions is a fundamental initial requirement to inform nexus related responses at the European level. Countries with challenges of malnutrition, economic water scarcity, or water limitations land investments should focus on food production for the national market. Foreign investors from EU countries should avoid targeting countries where there is a high risk of deforestation induced by the overexploitation of the land suitable for agriculture.
Ololade et al. (2017)	South Africa	To explore how the interconnectedness, interdependencies, and security of food, energy, and water systems can lead to new policy paradigms and to identify research needs for moving South Africa onto a sustainable development path.	WEF nexus for sustainable development	Influence policy pathways that address South Africa’s development whilst addressing water scarcity, food and energy insecurity	

Urban and Siciliano (2017)	China, Ghana, Nigeria Cambodia Malaysia	The aim was to highlight on China's role as a rising power in low carbon development specifically on hydropower in Africa and Asia.	Social and environmental sustainability. Food energy, water and land nexus. Environmental and social justice compensation and access to natural resources	Social and economic challenges and opportunities for foreign-funded dams Policies need to support local communities with formal processes through which communities can use to hold transnational companies accountable to these communities	Energy generation to meet community or development goals should embrace stakeholder engagement to address water governance issues and consider the effects on local communities
Adeel (2017)	Arab region Egypt Tunisia Libya Sudan Morocco Djibouti Somalia	Highlights the role played by water, food, and energy in regional security; it presents some inter-related drivers of change that impinge on regional security: the burgeoning population with a significant 'youth bulge' and accompanying widespread youth unemployment; the economic impacts as a result of globalization, particularly in food and energy sectors; the rise in extremist ideologies and their intersection with efforts to enhance democratic processes; and, geopolitical tussles that are often aimed at greater control of the region's various resources	Peaceful co-existence of Water food and energy nexus and regional security encompassing flow and access to resources, sustainable economic development and poverty reduction	There is need for quantifiable economic and social benefits of the Water-Energy-Food Nexus (WEF Nexus) to regional security, in the Arab, Region to inform policy and decision making	The priorities are: • Raising awareness and disseminating knowledge; • Improving the harmonization of public policies; • Examining the link between water and energy security; • Improving efficiency; • Increasing knowledge of technological choices; • Promoting renewable energy; • Integrating climate change and natural disaster factors in decision-making.

Udias et al. (2018)	Benin, Burkina Faso and Niger	Implement the E-water as a decision support system to support optimal management solutions that enhance food crop production at the river basin level. The DSS was applied in the transboundary Mekrou River Basin, shared among Benin, Burkina Faso and Niger	A decision support system to support water energy food and environment nexus (WEFE)	Support the development of agricultural strategies to optimize agriculture productivity in areas with shared water resources by combining agricultural inputs with a decision support tool for site-specific farming.	Strategies to support crop production should also take into consideration the balanced use of natural resources such as water by other sectors such as livestock production, urban settlements and energy
Nhamo et al. (2018)	SADC	The aim was to explore opportunities for the WEF nexus in promoting cross-sectoral policy linkage among water, energy and food sectors at a regional level to achieve regional integration and sustainable development.	WEF nexus conceptual and methodological model framework. The model explores the interactions between human and natural systems that maximise human-environmental security through WEF nexus.	The regional conceptual framework and model present opportunities for developing comprehensive analysis approaches, identify synergies in the nexus and assess multiple benefits and trade-offs across ecosystem service sectors.	The study recommends a set of integrated assessment models to monitor and evaluate the implementation of WEF nexus targets and propose the adaption of a regional WEF nexus framework
Mpandeli et al. (2018)	SADC	The objective of the review was to highlight the impact of climate change on water, energy and agriculture sectors in the SADC region, and explore opportunities for the WEF nexus in developing cross-sectoral sustainable climate change mitigation and adaptation strategies and plans.	Regional and international review on climate change impacts on WEF resources, adaptation opportunities, challenges and mitigation in the SADC region.	Climate change impacts are cross-sectoral and multidimensional, and therefore require cross-sectoral mitigation and adaptation approaches. WEF nexus approach offers opportunities to build resilient systems harmonise interventions and mitigate tradeoffs and hence improve sustainability.	The study recommended several climate change adaption strategies in the region, which include: - 1) Promoting climate-smart agriculture 2) Developing early warning systems 3) Integrated water resource management, 4) Promoting renewable energies with a low carbon footprint

					5) Increasing monitoring and modelling capacities across each of the WEF nexus.
Mabhaudhi et al. (2018)	SADC	Aim of the review was to assess the current status of irrigated agriculture in Southern Africa from a water-energy-food nexus perspective.	Review assessment of Africa's and southern Africa's visions for achieving food and nutrition security and the role of irrigated agriculture.	In this study, it was established that success irrigation expansion in the agro-based economies of southern Africa is reliant on holistic and systematic WEF nexus approach. Implementation of a WEF nexus approach would ensure that trade-offs with energy and water are mitigated whilst maximizing the synergies.	Recommendations From this study were the inclusion of smallholder farmers through investments in small-scale irrigation schemes that will assist in the development of resilient food systems and strengthening their capacity to adapt to climate variability and change.
Agyei et al. (2018)	West Africa	The aims to provide a better understanding of how NDCs might facilitate SDGs progress in West Africa, particularly across goal 1 (no poverty), 2 (zero hunger), 6 (access to clean water and sanitation), 7 (affordable and clean energy), 13 (climate action) and 15 (life on land).	Interactive situation analysis exploring key themes for adaptation and mitigation within Nationally Determined Contributions (NDCs) of 11 West African states and alignment to selected SDGs.	Establish coherence between policies in the water-energy-food sectors and contribute to the African Union's Agenda 2063, which details the development objectives for all African states.	Research gap identified a need to improve renewable energy sources, including biofuels, and conflicts across the water-energy-food nexus.
Pardoe et al. (2018)	Sub-Saharan Africa, Tanzania	The study examined how climate change is addressed in policy and how it is mainstreamed into water, energy and agriculture sector policies and the extent to which cross-sectoral linkages enable coordinated action.	Qualitative research approach on policy documents; A case study in Tanzania Interviews to identify progress and barriers to implementing climate change adaptation in	In Tanzania, the National Adaptation Plan of Action (NAPA) has successfully encouraged climate change mainstreaming into sectoral policies. Collaboration between nexus sectors provides a platform for cross-sectoral coordination and	The case study is relevant for many other countries in sub-Saharan Africa, particularly those pursuing agricultural intensification and hydropower development in the face of an uncertain future climate.

			practice across the 3 sectors	implementation of adaptation strategies.	
Yang et al. (2018)	West Africa	This study aims to analyse the sustainability of and tradeoffs across water-energy-food ecosystem nexus	Generic metrics to evaluate the sustainability of water availability for three water-dependent systems (food, energy and riverine ecosystem health).	Assessing the sustainability of the nexus from the perspective of water availability is limiting the ability to represent the sustainability of the overall nexus. Applications of cross-sectoral enriching the sustainability of the overall nexus to be considered and implemented.	Several future research directions can be explored, including 1) coupling water-food-energy models with multiple environmental indicators, 2) address agricultural production and incorporate multiple ecological indicators to better reflect riverine water demand.
Dombrowsky and Hensengerth (2018)	W & E. Africa and SE Asia	The aim is to investigate the role of regional organizations in the transboundary governance of the water-energy-food nexus related to hydropower investments along international rivers. To identify the role of regional organizations in governing hydropower-related WEF nexus impacts	Regime theory/neo-institutionalism in international relations – understanding nexus governance as a dynamic and recursive process involving state and non-state actors who establish.	Supports WEF security; nexus governance;	Recommends that while nexus impact of hydropower investments should be studied at the basin scale, it would be inadequate to limit the analysis of nexus governance related to hydropower to the basin scale
Yang and Wi (2018)	Eastern Africa	The aim is to develop a coupled modelling framework capable of explicitly quantifying natural and human components that affect the WEF nexus in the Great Ruaha River system.	WEF nexus competition is simulated using an advanced water system modelling approach and findings are visualized via interactive web-based tools	Supports water security with consideration of social-economic aspects of WEF nexus	Future work: to improve the prediction of impacts of different mitigation measures; ground surveys on the irrigation areas, intakes, main canals, and drainages points; topographical surveys of the

		To calibrate the model based on the pooled calibration with multiple targets of streamflow, water depth, and hydropower generation; provide an interactive web-based visualization tool			areas to improve the reliability of the simulated effects on downstream flows; design of a low weir to be studied from an engineering point of view to include viable technical options in the model.
Mwampamba et al. (2018)	Sub-Saharan Africa, South-east Asia and Latin America	The aim is to develop a theoretical and conceptual framework for analysing interlinks between charcoal, livestock, and hydrological processes where they co-exist. To analyse the isolated effects of charcoal production and livestock on hydrological processes and explore their combined effects	Use a systemic approach to analyse interlinks between charcoal, livestock, and hydrological processes. Scarce water resources for agricultural production, energy generation, and ecosystem services, i.e. *charcoal-livestock-water nexus*	Supports hydrological processes management and practice.	Further work: Assessment of current understanding of charcoal production effects on vegetation and soils in the tropics, in light of the possible effects that livestock may have on the system. Studies of livestock impact on vegetation to include the co-occurrence of charcoal in management systems.
Udias et al. (2018)	West Africa	Aim: Implementation of E-Water, an open software Decision Support System (DSS), designed to help local managers assess the Water Energy Food Environment (WEFE) nexus;	Water Energy Food Environment (WEFE) nexus	Supports WEF security; job creation;	Need to integrated information on costs associated with agricultural practices into the DSS.
Seeliger et al. (2018)	South Africa	Aim: To demonstrate how the nexus approach, when embedded in a farm budget model, can Contribute to understanding the relationship between water,	Water, energy and agricultural food production nexus	WEF security & management	Although the analysis proves that emphasizing the energy element of the

		energy and food affect farm can be profitable. To position the broad WEF nexus debate within the South African water sector To draw links between water, energy and agricultural food production within the Breede River Catchment.			water-energy-food nexus in a catchment management system can have positive impacts on food production and economic growth at the farm level, the need to include solar energy powered pumps or other supplementary forms of energy in future analyses
Matthews and Mccartney (2018)	Africa and Asia	Aim: To explore the challenges facing decision-makers with regards to building resilience and navigating risk within the water-energy-food nexus and dams.	Water-energy-food nexus and dams.	Creation of environmental and social costs (dam construction) including implications for the health, resilience and livelihoods of the poor; Sustainable Development Goals and the Paris Agreement;	Recommend the need to address challenges related to mitigating impacts across the nexus and social-ecological resilience
Ding et al. (2019)	Sub-Saharan Africa Case study examples include Senegal, Nigeria and South Africa.	To develop an analysis framework for evaluating the different interrelationships among water-energy-food (WEF) resources, services and health sectors.	The analytical framework is applied to make use of a data-driven approach for multiple sub-Saharan African countries which have notable WEF insecurity challenges. The data-driven approach uses a cross-validated stepwise regression analysis.	There is specific mention to South Africa which faces significant challenges to implement its water policy effectively. The work from this study can help guide analyses evaluating where in the WEF nexus the challenges exist.	There is a need to develop a cohesive framework that can clarify the different key linkages and guide the analyses. This can be done by introducing a WEF analytical framework that leverages a theoretical understanding of resource systems to better understand WEF nexus interactions.

Mabhaudhi et al. (2019)	Southern Africa	Apply WEF nexus analytical livelihoods model with complex systems to assess and understand rural livelihoods, health, and well being in southern Africa and recommend tailor-made adaptation strategies for the region and building resilient rural communities	This study adapted the WEF nexus analytical model developed by Nhamo et al to develop a WEF nexus analytical livelihoods framework, which was used to analyse and address the complex and interrelated nature of resource systems	This research identified the trade-off and unintended negative consequences for poor rural households' livelihood of current silo approaches, mechanisms for sustainably enhancing household water, energy and food security. Whilst providing direction for achieving SDGs 2, 3, 6 and 7.	Further studies should consider the link between WEF indicators and SDGs indicators for assessing the performance of the WEF nexus analytical model. Acquire more data at a household level and focus on the household scale analyses as this will translate to greater impact.
Gush et al. (2019)	South Africa	The study applied cutting edge measurement and modelling techniques to quantify the actual volumes of water used by apple orchards under current land and water management practices, and to propose a practical methodology for scaling up the water footprint information for irrigated crops from filed measurements to watershed scale to facilitate water resource management decisions	Blue, green and grey water footprints information, using the water footprint network approach up to farm-gate level, was determined for an apple (Malus pumila) orchard growing under Mediterranean climate conditions in South Africa.	This study showed that observations on volumes of water used by a particular crop will greatly improve the accuracy of water footprint calculations for products of that crop. The particular scale at which the assessment is done (farm or watershed) consequently has the potential to facilitate both on-farm water management planning and irrigation scheduling, as well as crop-specific water use allocation guidelines and sustainability improvements within watersheds.	Deciduous fruit produced in Mediterranean regions is highly dependent upon irrigation. This industry is one of the major users of water and facing increased competition for water. Research to improve the efficiency or productivity of water use is required. For the industry to grow sustainably and in parallel to other competing water users, water requirements for the industry need to be carefully considered, allocated and utilized in more efficient ways possible.

Ding et al. (2019)	South Africa Cape Town	To compare two different scenarios for responding to drought by using an agent-based model. The two scenarios were business-as-usual (BAU) and holistic-adaptive management (HAM).	A model was designed which represented various stakeholders from the food, water, energy and municipal sectors. This served as the testbed for comparing and simulating water-energy-food (WEF) system outcomes under different policy scenarios.	The different policy applications had different cost or tariff implications. Under the BAU policy, the City of Cape Town increases tariffs based on the current level of restriction. Under the HAM policy tariffs are set based on the necessary curtailment of consumption and the water price elasticity of demand and also makes use of the pre-drought monthly average of a reservoir. The HAM policy resulted in much stricter and steeper tariff hikes under less severe drought conditions but conserved more water over the longer term.	The simulations suggest HAM policy can alleviate the impact of drought on the availability of water for residential consumption, agricultural production and hydropower generation. More work is needed in addressing other smaller agents in each sector like inequality among residents.
Salmoral et al. (2019)	Eastern (Jordan) & Southern Africa (Zambezi River Basin)	The aim is to identify and evaluate unrealized complementarities between nexus governance and water diplomacy and discusses the benefits of integrating both for improved transboundary basin management.	Integration of nexus governance and water diplomacy for improved transboundary basin management	Nexus governance and water diplomacy, promotion of cooperation in the management of transboundary resources; also points to socio-political issues	Concludes that appropriate implementation of nexus governance requires further acknowledgement, evaluation and inclusion of evolving socio-political realities while recognising that there is no single, ideal and rational solution. There is a need to take into account cross-sectoral WEF agreements and diverse

					stakeholders' interests in future transboundary negotiations and discussions. Need to address institutional and political barriers for effective transboundary natural resource management. Lack of relevant impact-generation mechanisms To monitor effective changes in natural resource management and related policy.
Simpson et al. (2019)	Southern Africa	The aim is to critically review the Mpumalanga Province through the lens of the WEF nexus. Objectives: identify and investigate interactions and tradeoffs of WEF; analyses nexus interactions; draw conclusions on the existing or potential threats to WEF security in the province; recommend potential corrective actions needed to remedy possible threats to the WEF security	semi-quantitative WEF nexus assessment - trade-offs between resources	Supports resource security; Sustainable Development Goals; regional land use and mine closure strategy; Integrated Resource Plan	Recommends integration of key regulatory departments associated with the WEF nexus, together with industry, NGOs and the public, in a regional planning initiative to enable the region to balance its, and the nation's, competing requirements. Need for WEF nexus science and data to influence integrated public policy to promote long-term sustainability

Hameed (2019)	Egypt (Study focuses on 16 Arab countries but only 1 in Africa)	A comprehensive assessment to study and evaluates the emerging drivers of WEF systems in the region. The investigated drivers include water security, extreme events, economic growth, urbanisation, population growth, poverty, and political stability.	Socioeconomic and political drivers of water-energy-food (WEF) security in the Middle East	Policies need to address water resource security and planning or management strategies especially in the face of climate change and socioeconomic growth as this can likely increase political unrest in the region	Support water-efficient energy production
Nhamo et al. (2020)	South Africa	To develop an integrated analytical model to simplify the intricate interlinkages among water-energy-food (WEF) resources using South Africa as a case study.	The study defined WEF nexus sustainability indicators. Using the Analytic Hierarchy Process the analytical model was developed to establish quantitative relationships between WEF sectors.	This analytical tool can be used by policy and decision-makers to identify priority areas that need intervention.	The analytical tool only provides an overview and simplified view regarding which sectors need intervention in the WEF nexus. More the in-depth analysis is then also needed for sector-specific issues.
Laubscher and Cowan (2020)	Southern Africa	The aim is to elaborate on the linkage between algae-based sewage treatment and energy production to emphasize the net energy that can be gained using an already substantiated integrated algal pond system (IAPS) and the value of its co-products that include water for recycle and re-use and an organic nitrogen-rich liquid fertilizer	WEF nexus: products desired by primary industry (e.g. agriculture and horticulture) in the peri-urban space, position algae-based sewage treatment at the water-energy-food nexus.	Supports WEF security; generation of clean energy	Recommends production of organic liquid fertilizers of the NPK type, i.e. outcomes of algae-to-energy wastewater treatment.

APPENDIX 2: WATER ENERGY FOOD NEXUS QUESTIONNAIRE

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Water-Food-Energy

The water-energy-food (WEF) nexus has been identified as one of the approaches that can be used to improve understanding of the complex interactions among water, energy, and food systems. The WEF nexus is a systems-based approach that considers the interactions, synergies and trade-offs of water, energy, and food. The South African Weather Service in partnership with the University of KwaZulu Natal has been commissioned by the Water Research Commission (WRC)to take this project that focuses on the WEF nexus for southern and eastern Africa. The survey below seeks your expert input based on your knowledge of and experience in the study site to understand the interactions between the nexus components.

Consent to participate

If you are happy to participate, please complete and sign the consent form below.

1. I confirm that I have read and understood the provided information above and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.
3. I understand that my responses will be kept strictly confidential. I understand that my name will not be linked with the research materials and will not be identified or identifiable in the report or academic publication that results from the research.
4. I agree that my anonymised data will be kept for future research purposes such as publications related to this study after the completion of the study
5. I agree to take part in this interview.

__________________ __________________________

Respondent Date Signature

Sustainable livelihoods, Health & Well-being in the Vhembe District Municipality

Please select the number that best described to what degree do you agree with the following statements.

1-Strongly Disagree 2-Disagree 3-Neither Agree or Disagree
4-Agree 5-Strongly Agree

1. **The Vhembe District Municipality experiences scarcity of water, energy-food resources due changes in population growth & urbanization**

1	2	3	4	5

2. **The Vhembe District Municipality experiences scarcity of water, energy-food resources due changes in climate change hazards**

1	2	3	4	5

3. **The Vhembe District Municipality is a high-risk area and is vulnerable to extreme weather due to economic, and socio-environmental drivers of change**

1	2	3	4	5

4. **Communities in the Vhembe District Municipality have high exposure & are sensitive to the limited water, energy-food resources due to economic and socio-environmental drivers of change**

1	2	3	4	5

5. **The well-being of communities in the Vhembe District Municipality is impacted by weak government institutions**

1	2	3	4	5

6. **The Vhembe District Municipality experiences mortality rate that can be attributed to unsafe water, unsafe sanitation, and lack of hygiene**

1	2	3	4	5

7. **The malnutrition prevalent in the Vhembe District Municipality is associated to the food insecurity among the residents**

1	2	3	4	5

8. **Available & accessible freshwater resources in the Vhembe District Municipality can meet the resident's needs now & in future**

1	2	3	4	5

9. **Crops produced through irrigation in the Vhembe District Municipality can meet the people's needs now & in future**

1	2	3	4	5

10. The electricity accessible to people in the Vhembe District Municipality is enough to use now and in the future

1	2	3	4	5

11. Energy produced to support economic growth in the Vhembe District Municipality is enough for the municipality's needs now and in future

1	2	3	4	5

12. Households in the Vhembe District Municipality have access to nutritive and affordable food to meet their needs now & in future

1	2	3	4	5

13. Agricultural food production in the Vhembe District Municipality can meet the people's needs now & in future

1	2	3	4	5

Please select the number that best described to what degree do you agree with the following statements.

1-Strongly Disagree 2-Disagree 3-Neither Agree or Disagree
4-Agree 5-Strongly Agree

1) **The community/region experiences scarcity of water, energy-food resources due population growth & urbanization**

1	2	3	4	5

2) **The community/region experiences scarcity of water, energy-food resources due changes in climate change hazards**

1	2	3	4	5

3) **The community/region is a high-risk area and is vulnerable to extreme weather due to economic, and socio-environmental drivers of change for example land use change from agriculture to urban settlements**

1	2	3	4	5

4) **The community has high exposure & is sensitive to the limited water, energy-food resources due to economic and socio-environmental drivers of change**

1	2	3	4	5

5) **The community is able to recover from economic and socio-environmental disruptions (e.g. famine, floods, high food prices, conflict)**

1	2	3	4	5

6) **The wellbeing of the community is impacted by weak government institutions**

1	2	3	4	5

7) **The community experiences high mortality rate (deaths) that is due to unsafe water, unsafe sanitation, and lack of hygiene**

1	2	3	4	5

8) **The malnutrition that is common in the community is because of food insecurity among the residents**

1	2	3	4	5

9) **The available & accessible freshwater resources in the community can meet our needs now & in future**

1	2	3	4	5

10) **Crops produced through irrigation in the community can be sustained now & in future**

1	2	3	4	5

11) Population with access to electricity in the community can be sustained now & in future

1	2	3	4	5

12) The energy produced to spur economic growth in the community can be sustained now & in future

1	2	3	4	5

13) Access to enough and nutritive food by the population can be sustained now & in future

1	2	3	4	5

14) Agricultural production in the community can be sustained now & in future

1	2	3	4	5

Additional information during discussions

Proportion of available freshwater resources	
Percentage of population with access to potable water supply (drinking)	
Percentage of population with access to water for sanitation and hygiene	
Percentage of population with access to water for income diversification (irrigation, energy, etc.)	
Proportion of water used for crop production, livestock and forest products	
Proportion of water used for energy generation (hydropower, cooling, processing)	
Proportion of crops produced for food consumption	
Proportion of crops produced for biofuel and bioenergy	
Access to food and availability of markets and relief	
What are the main sources of energy?	
Percentage of population with access to electricity	
Proportion of energy used for water (abstraction, treatment)	
Proportion of energy used for food (harvesting, processing, transport)	
Proportion of energy produced for economic growth	
Prevalence of moderate/severe food insecurity in the population	
Status of poverty and malnutrition	
Proportion of sustainable agricultural production per unit area	
What are the main sources of income?	
Other sources of income?	
Percentage of employment	
Existing infrastructures for water, energy, food.	
Rate of population growth	
Access to social grants	
Proportion of land degradation and human intervention on the environment	
Health status and labour productivity	
Projects that have been undertaken on climate change, or energy or water programs	
How does the information filter down to the community	

APPENDIX 3: CAPACITY BUILDING AND KNOWLEDGE TRANSFER

Capacity building and knowledge transfer activities included scientific training of students for postgraduate qualifications, scientific papers published, and stakeholder engagement workshops. Capacity building also included the development of the SAWS project team members on different aspects of the projects including the use of the IWEF Tool and scenario planning. Research capacity was built by registering two students for post-graduate studies:

Name	Degree	Status
Nosipho Zwane	PhD Meteorology (University of Pretoria)	In progress
Thabo Makgoale	MSc. Geography and Environmental Management (North-West University)	Completed

The PhD student is working on the topic: Systematic Evaluation of the WEF Nexus Linkages from an Energy Perspective in Kenya (Maasai Mara) and South Africa (Vhembe District Municipality, Limpopo). She is progressing well. She has conducted fieldwork where she engaged stakeholders and collected some of the data that she will use in work.

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2. Zwane, N., Tazvinga, H., Botai, C., Murambadoro, M., Botai, J., de Wit, J., Mabasa, B., Daniel, S. and Mabhaudhi, T., 2022. A bibliometric analysis of solar energy forecasting studies in Africa. Energies, 15(15), p.5520.
3. Botai, C.M., Botai, J.O., Tazvinga H., Murambadoro, M.D., Nhamo, L., Ncongwane, K.P., Mengistu, M.G., Zwane, N., Wamiti, E., Mpandeli, S., Muthoni, M., Mabhaudhi, T. Assessment of rural livelihoods, health and wellbeing in Vhembe District Municipality, South Africa and Narok County, Kenya. Environmental Science & Policy. In press.