Assessing sustainable water, energy and food nexus smart innovations, technologies and practices in Luvuvhu and Nzhelele River catchments areas, Vhembe District Municipality, Limpopo province, South Africa.

By

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Abstract

The water-energy-food (WEF) nexus aids in comprehending the complex and ever-evolving connections between these three essential resources. Climate change and slow economic growth are triggering an increase in pressure on global WEF resources. These present an increase in levels of trade-offs and conflicts among the three resources. The implementation of the WEF nexus can improve resource security and promote sustainable development. However, its widespread adoption has been limited due to the absence of concrete strategies for its practical application. This study assessed the status of WEF nexus smart technologies, innovation and practices in Luvuvhu and Nzhelele River Catchments Areas, Limpopo Province, South Africa. Subsequently, face-to-face surveys were undertaken from 9 July to 30 November 2022 for individual households and focus group discussions (FGD) were conducted within communities under the Luvuvhu River Catchment Areas (Sambandou, Malavuwe and Tshakhuma); and Nzhelele River Catchment Areas (Siloam, Phadzima and Khalavha). A random sampling technique was utilized to select 93 households from a total of 180 targeted households. Key Informant Interviews (KII) were conducted with representatives from the local Department of Water and Sanitation, Eskom, the local Department of Agriculture and Rural Development, as well as local radio stations. During these interviews, data was collected through interview-administered questionnaires. The data obtained from the questionnaires was analyzed using IBM SPSS Statistics version 29, which facilitated the generation of response frequencies. Additionally, the ArcGIS Inverse Distance Weighting (IDW) spatial interpolation method was employed for spatial analysis. The results indicated that the sustainability of the water-energy-food (WEF) nexus depends on the resilience of each resource individually as well as within their respective sectors. The use of water and food smart innovations and practices was found to be slightly higher in the Nzhelele River Catchments Areas than it is in the Luvuvhu River Catchment Areas, with 55.9% (n= 55) and 38.7% (n= 36) of the respondents within the Nzhelele area and 47.3% (n= 44) and 31.2% (n= 29) in the Luvuvhu area using water and food smart innovations and practices, respectively. Moreover, the use of energy innovations and practices was found to be slightly lower in the Nzhelele area s (53.8%; n= 50) than it is in the Luvuvhu areas (59.1%; n= 55). However, most of the respondents in both study areas did not understand how WEF nexus works, whereas some practiced it based on the little knowledge they got from schools, workplaces and the internet. Results from assessing the influence of hydrology on the use of WEF Nexus smart innovations, technologies and practices showed that hydrology is a foundational element in the WEF Nexus as hydrological factors such as water quality, temperature variability and annual rainfall are very crucial in WEF Nexus, influencing the use of smart innovations and practices that could in turn improve the well-being of residents, the productivity of local agricultural and food systems while enhancing the sustainable management of water, energy, and food resources. The study results show that the use of water, energy and food in areas around Luvuvhu River Catchment and Nzhelele River Catchment are significantly impacted by hydrology. It was also noted that a significant percentage (90%) of the respondents reported that they depend on agriculture for survival, which is highly affected by hydrological conditions.

Knowledge about the WEF nexus needs to be transferred to people in rural areas through awareness and education. The results of this study can serve as a useful reference for developing regions to improve management of resources, facilitate sustainable development, and fill the existing knowledge gaps towards understanding how promising the WEF nexus innovations and practices are, and how these can be realized at the local community and household levels. Thus, potentially reducing the shortage of WEF resources.

Keywords

WEF Nexus; WEF Innovations and Practices; Smart Technology; River Catchment Areas; Resources Management.

Declaration

I, Phindulo Mphaphuli, student number 17004331, hereby certify this thesis to be my original work and has not been submitted for any degree at another university. The design and implementation presented herein are my own, and any contributions from other sources have been duly acknowledged and referenced. Furthermore, this research is conducted as part of the Water Research Commission (WRC) project C2020/2021-00392.

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Date: ________23 February 2025____________________

Dedication

This thesis is dedicated to me.

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Finally, I wish to thank myself for having the belief and determination to keep going.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

ANEMI - An ancient Greek term for the four winds, heralds of the four seasons

BI - Behaviour change interventions

CA - Conservation Agriculture

DEA - Data Envelopment Analysis model

DEM - Digital Elevation Model

DWA - Department of Water Affairs

EO-WEF - Earth Observation for Water-Energy-Food

ERDAS - Earth Resources Data Analysis System

ESKOM - Electricity Supply Commission

FAO - Food and Agriculture Organisation

FGD - Focused Group Discussions

GeoTIFF - Georeferenced Tagged Image File Format

GIS - Geographic Information System

GRASS - Geographic Resources Analysis Support System

GWPSA - Global Water Partnership – Southern Africa

HH - Household

IEA - International Energy Agency

IP - Innovation Platforms

IPCC - Intergovernmental Panel on Climate Change

KII - Key Informant Interview

MAP - Mean Annual Precipitation

MuSIASEM - Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism

PostGIS - Post Geographical Information System

QGIS - Quantum Geographical Information System

SATIM-W - South African Times-Water

SDGs - Sustainable Development Goals

SDTS - Spatial Data Transfer Standard

SI - Smart Irrigation

SINT - Sustainable Intensification

UCT - University of Cape Town

UK - United Kingdom

WEF nexus - Water-Energy-Food

WTPsWater treatment plants

WU - Water Utility

WWAP - World Water Assessment Program

WWTPs - Wastewater Treatment Plants

CHAPTER 1: INTRODUCTION

1.1 Background

Water-energy-food (WEF) nexus is an intersectoral approach that is used to define the interrelationship between water resources utilized to produce energy and foods. Energy is a critical input for water extraction, purification, and conveyance, as well as for the production and distribution of food (Pradhan et al., 2020). Webber (2016) stated that WEF resources are interdependent to an extent that with finite energy, there is finite water through desalination plants and deep wells. With finite water, more dams can be built to produce energy through hydropower and to irrigate food and energy crops. The WEF nexus takes a comprehensive, system-wide perspective, acknowledging the inherent interconnections between water, energy, and food in resource management. This approach aims to highlight both trade-offs and synergies while concurrently considering social and environmental impacts.

According to Hoff *et al*. (2017), the nexus of WEF nexus presents valuable opportunities for a diverse range of stakeholders including policymakers, businesses, investors, NGOs, and the general populace to address three interconnected global security challenges: access to water resources, sustainable energy, and food security. Nevertheless, significant disadvantages persist in conducting the necessary research for effectively implementing the nexus. One key issue is that nexus boundaries often do not align with conventional management or administrative divisions, such as Cities, river valleys, or political territories (Perrone *et al*., 2011). These misalignments present considerable obstacles the collection and analysis of data related to the interactions among different nexus components.

The nexus literature recognizes that successfully implementation of this approach necessitates coordinated integration, both vertically across different levels of government and horizontally among various societal sectors. It highlights the importance of institutional linkages and effective coordination mechanisms to achieve this integration (Scott, 2017 and Weitz *et al*., 2017). However, due to the complexities arising from these vertical and horizontal interdependencies, scholars have identified numerous impediments to the integration of the nexus approach into decision-making processes.

South Africa is predominantly characterized by a scarcity of essential resources. Its water resources are under significant strain, the extent of irrigable land is limited and the energy sector confronts considerable challenges stemming from low water availability and pressure from greenhouse gas emissions. This situation necessitates significant trade-offs among the WEF components. Population growth, urbanisation, geopolitical factors, and globalisation, coupled with economic growth, are intensifying the pressure on WEF resources. The security of these three resources is vital for promoting efficient, equitable, and sustainable development. WEF security should be investigated through the lens of an interconnected nexus because the security of one resource can bolster the security of the others, while a deficit in one can precipitate scarcities in the others. Rasul and Sharma (2016) highlight that understanding the connections and interdependencies within the WEF nexus presents significant opportunities to enhance resource efficiency, foster collaboration, and improve policy coherence among the three sectors.

According to the Food and Agriculture Organization (FAO, 2014), the WEF nexus has emerged as a valuable framework for understanding and managing the intricate interconnections within global resource systems. It is essential for attaining multiple social, economic, and environmental objectives. The approach focuses on balancing the competing demands and interests of different resource users while ensuring the preservation of ecosystem integrity. It is evident that the WEF nexus components are linked in such a way that an impact on one resource often affects one or both of the others; with increasing demand, this linkage is now more pronounced. Rasul and Sharma (2016) emphasize that understanding the linkages within the WEF nexus can create opportunities to improve resource use efficiency, strengthen cooperation, and enhance policy coherence among the three sectors.

The present study thus assessed WEF nexus smart technologies, innovations, and practices that can be implemented to ensure sustainable resources for all three. This will, in turn, help to secure resource sustainability for both present and future generations.

1.2 Problem statement

The depletion of natural resources is a global problem. Given the finite nature of these resources and an increase in demand, resources are depleting at a faster rate. For the past decades, resources have been managed independently as silos which have proven to be unsustainable because they are interconnected and the impact on one directly affects the others. (Simpson *et al*., 2019). Therefore, a more holistic and sustainable approach is imperative, one that utilizes a multi-centric philosophy where each sector receives equal consideration.

South Africa contends with water scarcity, and only approximately 13% of its land is suitable for Agriculture. Exacerbating this situation, much of this arable land overlaps with areas rich in minerals like coal. Ololade *et al*. (2017) indicated that with water being a precious resource, around 30% of the country's crops rely on irrigation, which accounts for approximately 75% of the nation's water used for agricultural purposes. Ross (1999) argues that, unfortunately regions with abundant natural resources often face deep challenges such as social disparity, unrest, poverties and instability. To ensure sustainable development, an approach with strong integration in managing these vital resources is essential.

Limpopo is a province prone to drought and faces drought-related challenges periodically. Maponya and Mpandeli (2012) note that severe droughts have resulted to a low water supply for irrigation in the province, which has a negative impact on the agricultural sector. The study area is semi-arid and depends on groundwater for community supply and on rainfed agricultural practices, with a prolonged decrease in rainfall. Communities within the area under study rely on groundwater to solve agricultural and water shortage challenges. This dependency becomes problematic as groundwater resources are approaching critical levels of depletion. The study area is semi-arid and is characterised by low, unreliable rainfall, which results in decreased agricultural production, shortages of drinking water and low groundwater yields. Therefore, the identification of locally appropriate technologies, innovations and practices is imperative.

The Nzhelele Regional Water Scheme, within the Nzhelele River Catchment Area, depends on boreholes that utilize diesel engines or handpumps (Musetsho, 2008). Furthermore, new boreholes are required to be drilled and installed regularly as existing ones are drying up due to the increased population and the total water requirements (Muavhi *et al*., 2021). Thus, energy is required to ensure water availability for both household use and agriculture. The Deterioration of water quality and quantity in this area already has a negative impact on water security, impacting negatively on agricultural practices and electricity production and poses danger for environmental and public health.

The Luvuvhu River Catchment Area is subject to flooding resulting from extreme precipitation events, with intensities exceeding 15 mm per hour (Mathivha *et al*., 2016). This, in turn, impacts process performance and decreases removal efficiencies in wastewater treatment plants and energy production (Philips *et al*., 2012). Heavy rainfalls lead to the gradual depletion of headwaters and cause land degradation, affecting food production. Ndou *et al.* (2019) acknowledged the significance of restricting water extractions and alterations to river flow patterns in the LRC areas. It was emphasized the need to establish environmental regulations that protect and sustain the river's ecosystem characteristics and functions, aiming to prevent water resource depletion while also considering the impact on other resources.

The scarcity of WEF resources presents a growing challenge, exacerbated by population growth and increasing demand. Consequently, lack of WEF nexus approach in rural areas exacerbates problems with water shortages, electricity, and food production.

1.3 Rationale of the study

As reported by the FAO (2012), agriculture is responsible for roughly 70%of worldwide withdrawals of water. The WWAP (2014) stated that approximately 75% of industrial water use is dedicated to produce energy. The production of food as well as distribution utilize about thirty percent of global energy (WWAP, 2012), and water plays a vital role in ninety percent of worldwide electricity production (WWAP, 2014). Thus, implementing smart technologies, innovations, and practices on one resource will also bring change to other resources. For instance, sustainable practice of agriculture saves energy and water by lowering the use of fertilizers that energy consuming and increasing soil water storage as well as groundwater recharge.

The study is further motivated by the persistent tension among food and nutrition security, energy security and the deteriorating water quality. The WEF are the main three resources upon which humanity relies for survival. Therefore, when these resources deteriorate, it threatens both environmental sustainability and human well-being. Viewing these resources as a central hub ensures that no single sector dominates the others and encourages consideration of all resources in the decision-making process.

While the conceptual framework of the WEF nexus is increasingly recognized (Granit et al., 2013; Young et al., 2015), a significant gap persists in the empirical understanding and practical application of nexus dynamics, particularly at local and regional scales. Granit et al. (2013) indicated that WEF interactions can lead to synergies or conflicts. However, Young et al. (2015) acknowledged that a comprehensive understanding of these dynamics is often limited, leading to suboptimal policy and management outcomes that can compromise the security of these three sectors. What remains inadequately understood are the specific mechanisms and contextual factors that determine whether interactions result in synergy or conflict within unique socio-ecological systems. This study aims to address this by investigating these interactions within the specific context of the Vhembe District.

According to Flammini et al. (2014) for the FAO indicate that by 2050, global demand will necessitate approximately 60% more food and 80% more energy, with global water withdrawals expected to increase significantly by 2025. This highlights an urgent need for innovative solutions, yet there is a paucity of research focused on the suitability and scalability of specific technologies, innovations, and practices within resource-scarce, rural, and developing country contexts. The current study addresses this by focusing on identifying and assessing locally appropriate WEF smart innovations.

The imperative for WEF nexus capacity building in Southern Africa, underscored by the 2021 WEF Nexus Masterclass (GWPSA), signals a regional prioritization of enhancing knowledge for WEF security amidst mounting pressures from climate change, urbanization, and ecosystem degradation. Despite this regional focus, a critical knowledge gap exists regarding the practical implementation of WEF nexus approaches in the rural settings of Southern Africa. Several researchers, including

Conway (2015), Hilda (2019), and Simpson (2020), have conducted research in the Vhembe District. However, their work has predominantly involved reviews of the WEF concept, its evolution, and development, rather than empirical investigations into on-the-ground implementation and the efficacy of specific interventions. This study directly confronts this gap by shifting the focus from theoretical review to the identification and assessment of tangible WEF smart innovations, technologies, and practices currently or potentially in use within the selected rural areas.

Biggs et al. (2014) noted that WEF nexus studies have been limited in exploring the explicit connections between nexus dynamics and local livelihoods. This is a crucial omission, as the sustainability and adoption of any intervention are intrinsically linked to its impact on and integration with the livelihood strategies of local populations. Specifically, what is not well understood is how different WEF technologies and practices are perceived, adopted, or resisted by rural communities, and what their tangible impacts are on livelihood security in areas like the Vhembe District. This study aims to contribute to filling this gap by assessing practices within communities and using GIS to map their distribution, providing a basis for understanding their integration into the socio-economic fabric of the region. The GIS-based mapping will further address a gap in the spatially explicit understanding of where and how different WEF nexus innovations are being applied, and how these patterns relate to varying hydrological conditions within the study catchments.

1.4 Objectives

1.4.1 Study main objective

The main objective of the study was to identify and map the WEF nexus smart innovations, technologies and practices, their inter-linkages and how they are influenced by the hydrology of the study area.

1.4.2 Study specific objectives

The following were the study-specific objectives:

- To identify WEF nexus smart technologies, innovations and practices in the study area,

- To map and compare WEF nexus smart technologies, innovations and practices in different parts of the study area using GIS.

1.5 Research questions

The following research questions guided the study

- What are the WEF nexus smart technologies, innovations, technologies and practices in the study area?
- What are the similarities and/or differences in smart technologies, innovations, and practices used in the Nzhelele and Luvuvhu River Catchment areas using GIS

1.6 Description of the study area

1.6.1 Location

The study area comprises two catchments, the Nzhelele (A8) and Luvuvhu (A9) River Catchments (Figure 1.1), located in the Vhembe district municipality, Limpopo Province. The NRC lies on the lee ward side of the Soutpansberg Mountains, positioned at coordinate: 22°53'15.8" S; 22°54'5" S and 30°11'10" E and 30°11'23.5" E. In contrast, the LRC is at the windward of the mountain, between latitudes 22°25'32" S and longitudes 31°18'25" E.

Six villages were selected from these catchment areas. According to the 2011 Census, Tshakhuma Village spans 11.62 km² with a population of 17,371 people across 4,273 households (367.72 per km²). Sambandou Village covers 203 km², with a population of 826 people across 201 households (98.92 per km²). Malavuwe Village is 2.78 km² in size, with 2,362 residents living in 579 households (208.03 per km²). Siloam Village with an area of 2.93 km², a population of 2,049, and 456 households (155.55 per km²). Khalavha Village spans 5.97 km², with 3,237 residents and 822 households (137.77 per km²). Lastly, Phadzima Village covers 2.93 km², with a population of 4,966 and 1,153 households (393.65 per km²).

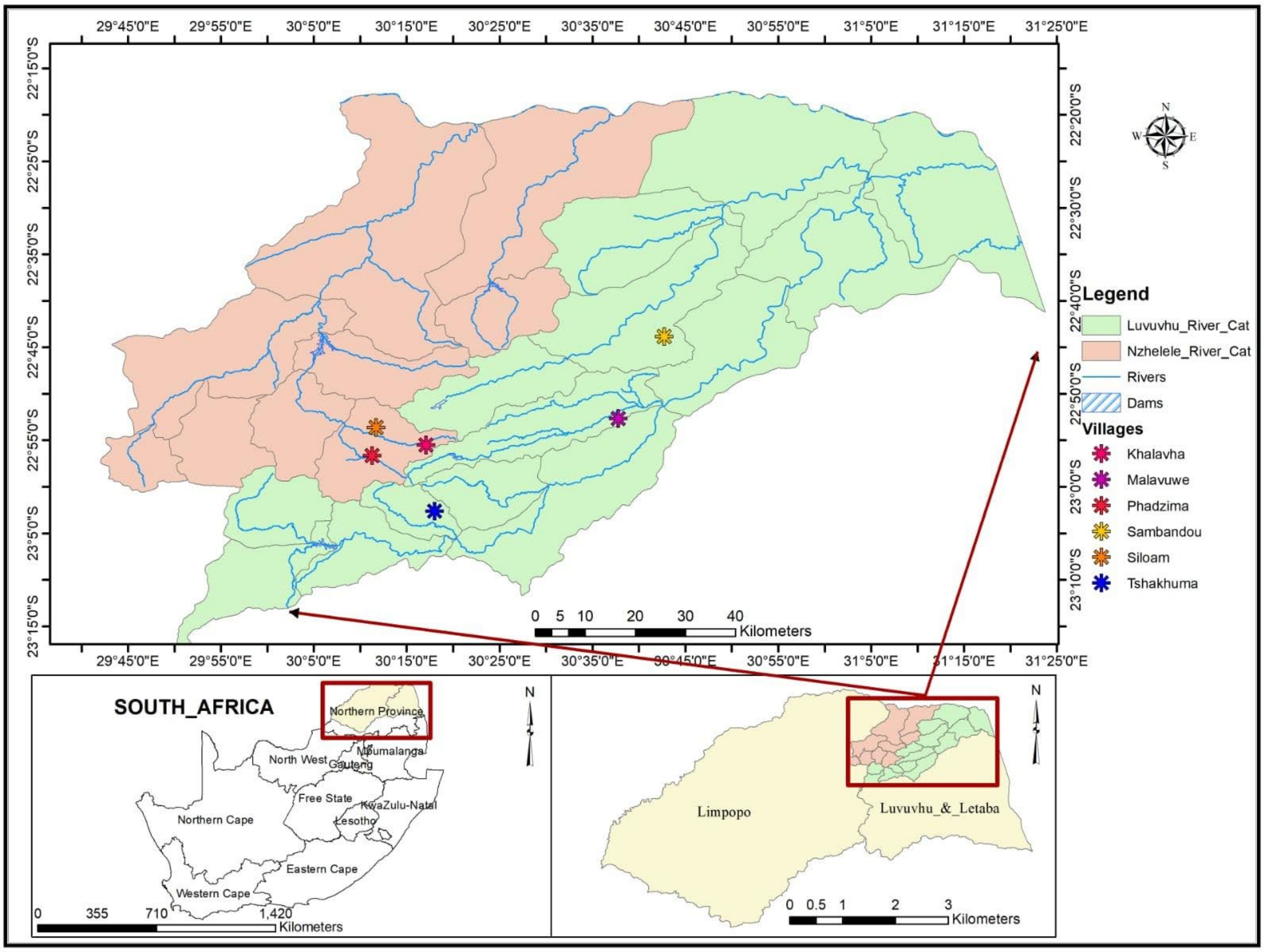

Figure 1.1: The study area

1.6.2 Geology

The area of study is located within the highly faulted Soutpansberg Group, which dates back to the Mokolian age (Figure 1.2). According to Makungo and Odiyo (2017), this group is part of the fractured crystalline basement aquifers in Limpopo Province, South Africa. The dominant rock types in the Soutpansberg system are quartz sandstone, quartzite, and sandstone, and there are some igneous intrusions of basalt and dolerite. This group of tectonic, wedge-shaped rocks, which are about 1.7 billion years old, forms rugged, mountainous terrain.The Soutpansberg Group consists of a volcano-sedimentary succession, comprising seven formations (Brandl, 1999).

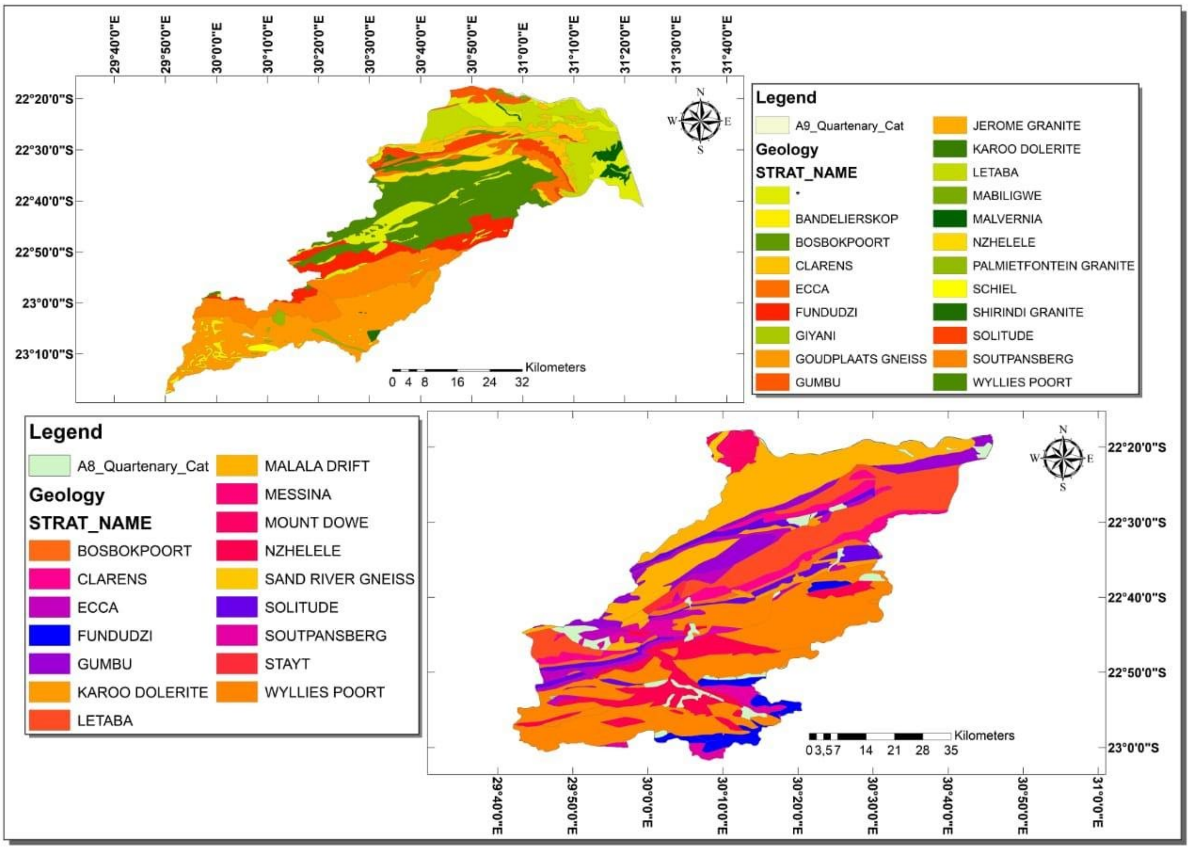

Figure 1.2: Geology of the study area

1.6.3 Hydrology

The NRC area experiences an average annual rainfall of 300–400 mm, with rainfall occurring seasonally from October to March during the summer months. The LRC area experiences varying mean annual precipitation (MAP), ranging from 1800mm its mountainous northeastern side to just 300 mm where it meets the Limpopo River in the east (Kagoda and Ndiritu, 2009). Located in the province's north, LRC drains the area with its main stream flowing from the northeast into Kruger National Park and subsequently joining the Limpopo River.

1.6.4 Climate

Nzhelele Valley is situated in a semi-arid region, wherein daily maximum temperatures typically range from 20°C - 40°C during the wet season and between 12°C and 22°C during dry season. The area experiences warm, wet seasons with temperatures reaching up to 40°C, particularly between March and October, leading to high evaporation (Edokpayi *et al.*, 2018). The highest rainfall is observed between January and February, while the cold and dry seasons extend from April to September. The climate of the Luvuvhu River Catchment Area is categorized as wet semitropical, with a semitropical dry forest bio-zone. During summer, on a daily basis, temperature ranges between 25-35°C, whereas in winter, they vary between 15°C and 26°C (Mzezewa *et al.*, 2010).

Table 1.1: Climatic statistics for the study area

Feature	Nzhelele River Catchment Area	Luvuvhu River Catchment Area
Region Type	Semi-arid	Wet Semitropical (Semitropical dry forest bio-zone)
Wet Season	Warm, Wet seasons (March-October)	Hot weather (March-October)
Dry Season	Cold, Dry (April - September)	Cooler and dry (Jun–Aug)
Daily Max Temp (Wet season)	Ranges from 20°C- 40°C	Ranges from 25°C- 35°C
Daily Max Temp (Dry season)	12°C - 22°C	Ranges from 15°C and 26°C
Highest Temps	Up to 40°C during summer	Up to 35°C during summer
Average Rainfall	300–400 mm	400–600 mm in the western/lowland area Up to 1,200 mm or more in the mountainous regions
Highest Rainfall months	January - February	October to March).
Evaporation	High	High

1.7 Chapter Summary

This chapter has outlined the background of the study based on a review of existing literature regarding the WEF nexus. It further indicates the motivation, illustrated he justification for the study, and provided the key objectives the research aimed to achieve.

CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

The chapter aims to review the nexus of WEF. emphasizing the interrelationships among its components. It introduces the operational definition of nexus innovation and organizes the reviewed literature according to the study's specific objectives. The review offers both a systematic and theoretical analysis of smart technologies, innovations, and practices within the WEF nexus, highlighting existing knowledge gaps and areas for improvement.

2.2 Smart innovations

Smart innovation refers to the kind of innovation that incorporates knowledge, intelligence and technology with sustainability. According to Howlett *et al*. (2018), smart innovation is very critical to the future well-being of society and the environment and driving economic growth while providing solutions to problems without creating more problems. Innovations are regarded as a central tool of sustainability policies, and they develop future visions into technological solutions while enabling a win-win framing of complex sustainability issues.

2.2.1 Smart innovations at the household level

Approximately 60% of the population in southern Africa resides in regions with restricted accessibility to essential provisions and facilities, including safe and cleaned water, affordable and sustainable energy, and nutritious food (Mabhaudhi *et al*., 2019). Despite technological advancements and their potential benefits, few studies have examined users' perceptions and acceptance of smart household technologies (Pliatsikas and Economides, 2022). These technologies can help regulate and reduce household energy consumption. While they can lower water, energy, and food (WEF) resource costs, the initial expenses for purchasing, installing, and maintaining them remain high.

Willis *et al*. (2011) highlighted that a lack of awareness regarding the necessity to conserve WEF, along with aging infrastructure, contributes to resource losses, leading to environmental, economic, financial, and socio-ethical consequences. To promote the sustainable use of WEF resources in buildings across both rural and urban areas, a smart technology project was developed, featuring a real-time water consumption monitoring and processing system (David *et al*., 2022). This system records users' water consumption data at the connection point to the distribution network and transmits it to a cloud platform, where the information is analysed to provide insights for end users, Water Utility (WU), and its customers. Implementing smart household systems requires the integration of various components, including hardware, software, network connections, and sensors. Amer *et al*. (2014) emphasized, the fundamental necessity for innovative energy-saving technologies at the household level. The dialogue between these authors suggests that successful smart household innovation requires a multi-faceted approach, addressing not only technological development but also socio-economic barriers, user engagement, and foundational infrastructure.

2.3 Nexus innovations

Nexus innovations, as defined by Larkin *et al*. (2019), involve developing technologies or practices to mitigate the adverse effects of WEF provisioning while tackling interconnected challenges like climate change. This concept extends beyond mere technological fixes, aiming for practical resource management and strategic solutions with lasting positive impacts on WEF resources. The underlying premise, as suggested by the general discourse on WEF nexus innovation, is that such integrated solutions can significantly reduce negative environmental impacts and address common challenges across WEF sectors by considering environmental health comprehensively.

If established extensively, these smart innovations, technologies and practices can thoroughly reduce the negative impacts on WEF resources as well as their provision. The WEF nexus innovation has been introduced to provide more simple and disruptive solutions to the major and most common challenges regarding the WEF sectors while taking into consideration environmental health.

The significance of nexus innovation consists of recognizing the interconnections between various resource sectors and understanding the cross-sectoral impacts of management and innovation (Sharmina *et al*., 2016). As a result, nexus research plays a crucial role in discussions by offering an integrated approach to addressing global challenges such as poverty, resource depletion, and climate change. Fam and Lopes (2015) emphasized that technological innovations are particularly relevant in this context because of job creation for investigation and learning, potentially disrupting inefficient and environmentally harmful production and consumption patterns.

Innovation can take different forms, including radical, incremental, architectural, and modular innovations, some of which provide advantages across all three nexus sectors. These innovations help tackle specific sectoral issues while also addressing broader challenges. Each type of nexus innovation contributes to lower the environmental impacts of managing resources and enhancing adaptive responses to environmental changes. Figure 2.1 illustrates the complex interactions within WEF systems and the development of sustainable strategies. It also provides examples of the interconnections between these three resources, aiding in a deeper understanding of the study's objective evaluating resource sustainability for both the present and future generations.

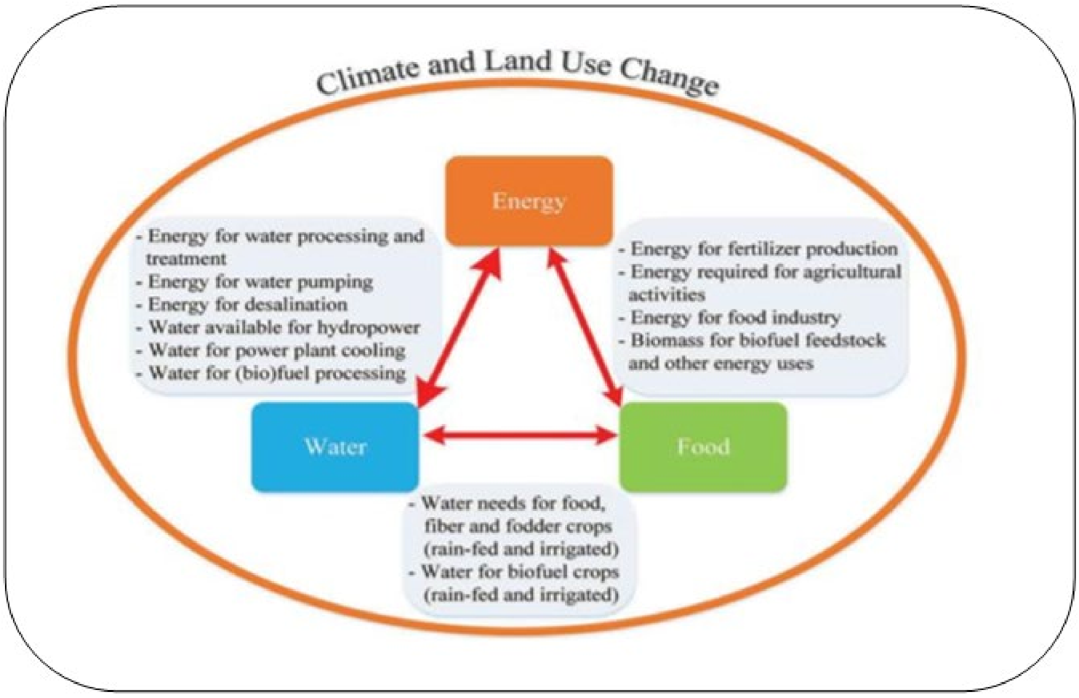

Figure 2.1: Example of WEF interconnectedness (*Adopted from Liu et al., 2017)*

A significant area of debate, or at least a persistent observed disconnect, is highlighted by Rasul (2016) and White *et al*. (2017), who note that despite the acknowledged interconnectedness of WEF systems, decision-making and policy planning within each sector typically occur in isolation. This observation is echoed by a chorus of researchers (Scott *et al*., 2011; Hoff, 2011; Flammini *et al*., 2014; Scott, 2017), who collectively argued that effective risk management and benefit optimization necessitate an understanding of not just physical connections but also crucial institutional linkages. This points to a critical gap between conceptual understanding of the nexus and its practical governance, suggesting that innovations in institutional frameworks and policy coherence are as vital as technological ones.

2.3.1 The dynamic of the WEF nexus framework

The dynamic nexus framework illustrates the interactions among three sectors and the nexus core, which encompasses the key drivers of the WEF sectors and cross-sector feedback. This framework simplifies the variables within the nexus core by focusing only on climates variation and population development as the primary factors influencing ecosystem services. The framework's emphasis on the need for decision-making teams and researchers to consider sectoral interdependencies directly addresses the siloed approach criticized by Rasul (2016), Scott *et al*. (2011). It also represents impacts on sectors and outcomes while regulating the attributes of core drivers, ensuring continuous interactions. The framework highlights three distinct entry points that introduce interests that are specifical for sectors. The approach promotes collaboration across sectors to prevent adverse trade-offs and inadvertent consequences. It emphasizes the need for decision making team and researchers to consider sectoral interdependences. Figure 2.2 presents WEF flow.

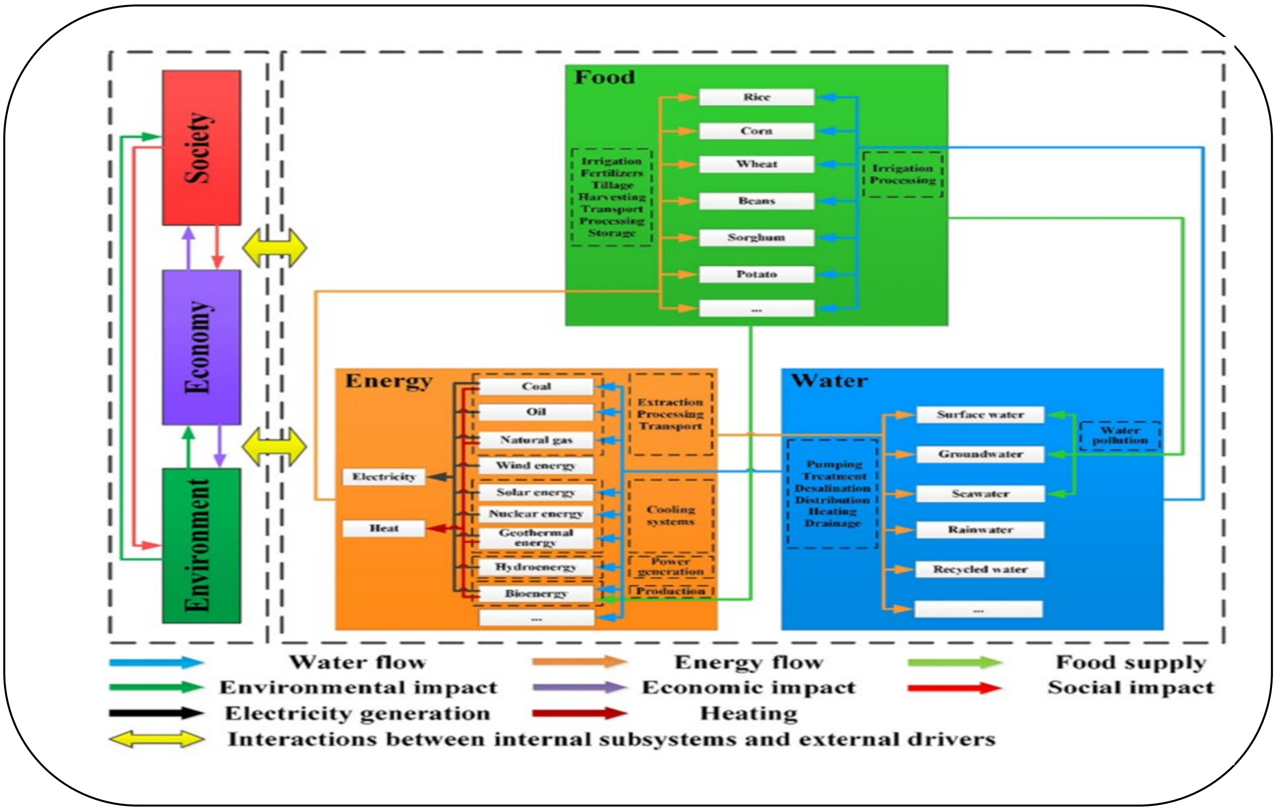

Figure 2.2: Summary of the WEF nexus (Adopted from Albrecht et al., 2018)

2.3.2 Understanding the dynamics of innovation in WEF

Research on the nexus for WEF has prolonged both educationally and geographically, leading to advancements in the conceptual framework, classification of challenges, and methodological developments, particularly since the 2011 Bonn nexus Conference (Endo *et al*., 2020). The WEF nexus framework provides insight into the interconnected nature of these three critical resources, enabling the implementation of smart innovations which improve WEF security while supporting a sustainable development.

The nexus approach comprises two key dimensions: interdisciplinary and transdisciplinary. The interdisciplinary aspect focuses on the intricate relationships among WEF resources, systems, and sectors, emphasizing trade-offs and synergies. Meanwhile, the transdisciplinary dimension fosters collaboration among diverse stakeholders, improving governance across sectors by integrating systems thinking into policymaking and balancing competing interests (Endo *et al*., 2020). This approach promotes long-term sustainability and resilience by preparing for systemic shocks through scenario planning (Naidoo *et al*., 2021).

A critical step in implementing the WEF nexus is transitioning from theoretical concepts to practical applications, ensuring integrated resource management (Naidoo *et al*., 2021). This framework represents a necessary shift towards a nexus-driven strategy that addresses unsustainable growth patterns and resource limitations, ultimately ensuring secure access to essential services. Figure 2.3 illustrates the dynamic interactions within the WEF nexus and how each resource influences the others.

(a) Energy

Energy is a measurable property that can be transferred to an object or a physical system. It exists in various forms, such as heat and light. According to the law of conservation of energy, while energy can change from one form to another, it cannot be created or destroyed. The total amount of energy remains constant during these transformations. Thus, the current study focused on electric energy as well as fuel and biofuel. Amegah and Jaakkola (2016) and IEA (2020) state that energy innovations and technologies are increasing rapidly, although about approximately twenty-five percent of the world's population continues to depend on traditional solid fuels for cooking, lighting, and heating.

(b) Energy for water

The operation of water treatment plants (WTPs) demands significant energy. A study conducted by the University of Cape Town (UCT) for the Water Research Commission estimated that wastewater streams in South Africa could yield 10 GWTH of recoverable energy, equivalent to 7% of Eskom's current electricity supply. Among wastewater treatment processes, nitrogen removal is particularly energy-intensive, with approximately 77% of the total electricity used in conventional wastewater treatment plants (WWTPs) dedicated to aeration during the activated sludge process, including nitrification (McCarty et al., 2011; Svardal and Kroiss, 2011). Rycroft et al. (2013) highlighted the significant energy demands of WWTPs, noting that actual consumption varies depending on wastewater composition and treatment methods. One study estimates that treating municipal wastewater requires about 600 kWh per megalitre. WWTPs are estimated to account for 1% to 3% of electricity consumption in developed countries and 0.5% to 2% in developing nations (Madhumati *et al*., 2020). The present study will show how energy is used for the extraction of water, treatment and transportation (Figure 2.3). Water treatment requires a huge amount of energy in different stages, including collecting water from the source, pumping, purification, handling, storage and disposal, amongst others.

(c) Energy for food

The production of agriculture is highly dependent on energy deprived from fossil resources with direct fuel and electricity utilisation being essential for carrying out various crop production practices (Baptista *et al*., 2013). Modern agricultural activities require energy input at all stages of production, including direct use of energy in machines utilised for farming, cultivation, management of water, irrigation, and cultivation. Post cultivation energy consumption includes energy which is used for the processing of food, storing and transportation to different markets or households. Some farming industries rely heavily on Eskom electricity to run their operations. Still, load-shedding has recently jeopardised production in energy-intensive and irrigation-dependent agricultural industries such as grains and agro-processing industries, among others. This study focused on the energy which is used for production, transportation and irrigation, which is shown in Figure 2.3.

(d) Water for energy

Siddiqi and Anadon (2011) state that water consumption in the sectors of energy production mainly takes place in two key sections: production of fuel and power generation. This process utilizes various technologies, each with distinct water usage requirements. When examining water use in energy production, steam plays a crucial role in driving turbines for power generation, while water is also essential for cooling, as it helps in condensing steam at the turbine exhaust. According to the DOE (2006), the heat foundation for these systems can be derived from fossil fuels (such as coal, oil, or natural gas), biomass (such as wood or waste), solar power, or geothermal energy.

In dry areas, shortages of water for cooling might result in low electricity production prompting the decision to place a power plant near a dependable water source, transport fuel instead, or opt for energy sources that require less water for cooling.

(e) Water for food

According to Faures *et al*. (2007) agricultural production is highly reliant upon water, which plays a significant role in food security. Agricultural irrigation accounts for 20 percent of the area cultivated and grows 40 percent of food worldwide. On average, agricultural irrigation has at least twice the production per area of land than rainfed agricultural activities, leading to more intensive production and crop diversification.

According to Molden (2011), with increasing populations, changing geographies, and dietary patterns, agriculture and food production are facing formidable challenges in the coming future. Such issues of water availability and its use are core to understanding and addressing these challenges. The significant rise in competition for water resources impacts negatively on agriculture as agricultural production highly depend on water resources for irrigation; thus, preserving water resources results in sustainable agricultural production.

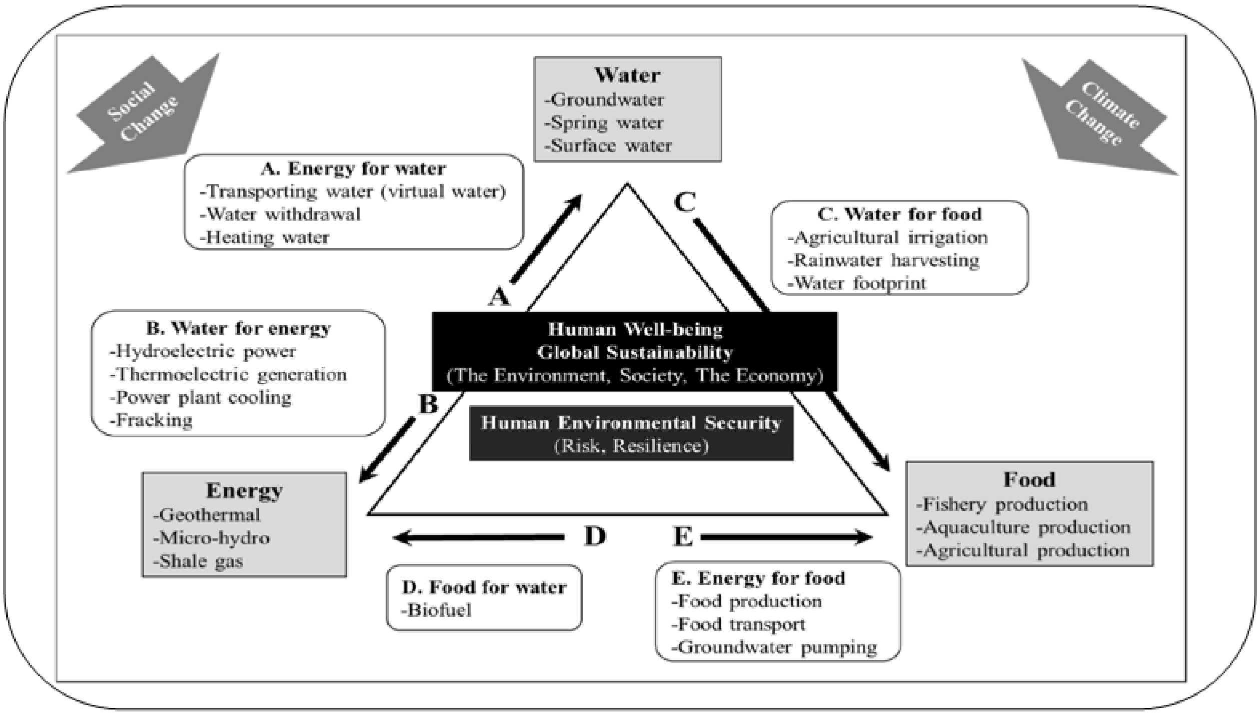

Figure 2.3: Dynamics of the WEF nexus (Adopted from Scot et al., 2021)

2.3.3 The impact of climate change on the use of WEF resources.

Southern Africa is highly susceptible to climate inconsistency and change as a result of several factors, including climate-sensitive industries dependent like agriculture and fisheries, inadequate resources for the inadequate, adaptation infrastructure, weak frameworks, and lowered adaptive capacity (Thornton *et al*., 2014; Nhamo *et al*., 2019). According to Mpandeli *et al*. (2018), the region's WEF resources are predicted to be among the most impacted by fluctuations of the climate. According to Nhamo *et al*. (2018), Africa hosts the largest proportion of people vulnerable to climate change, where chronic WEF insecurity and widespread malnutrition persist. Agricultural production is particularly at risk due to its heavy reliance on rainfall.

Niang *et a*l. (2007) stated that climate forecasts for southern Africa suggest that economic water shortage could intensify by 2025. According to the Intergovernmental Panel on Climate Change (IPCC), Parry et al. (2007) project that by 2020 and 2050, people ranging from 75–250 million and 350–600 million Africa, respectively, will experience heightened water stress, as illustrated in Figure 2.4. Furthermore, climate models suggest that if no action is taken to reduce greenhouse gas emissions, Africa may only be able to meet 13% of its food demand by 2050. Significant shifts are already occurring across various sectors, including agriculture, water, energy, biodiversity, and health (Niang *et al*., 2014).

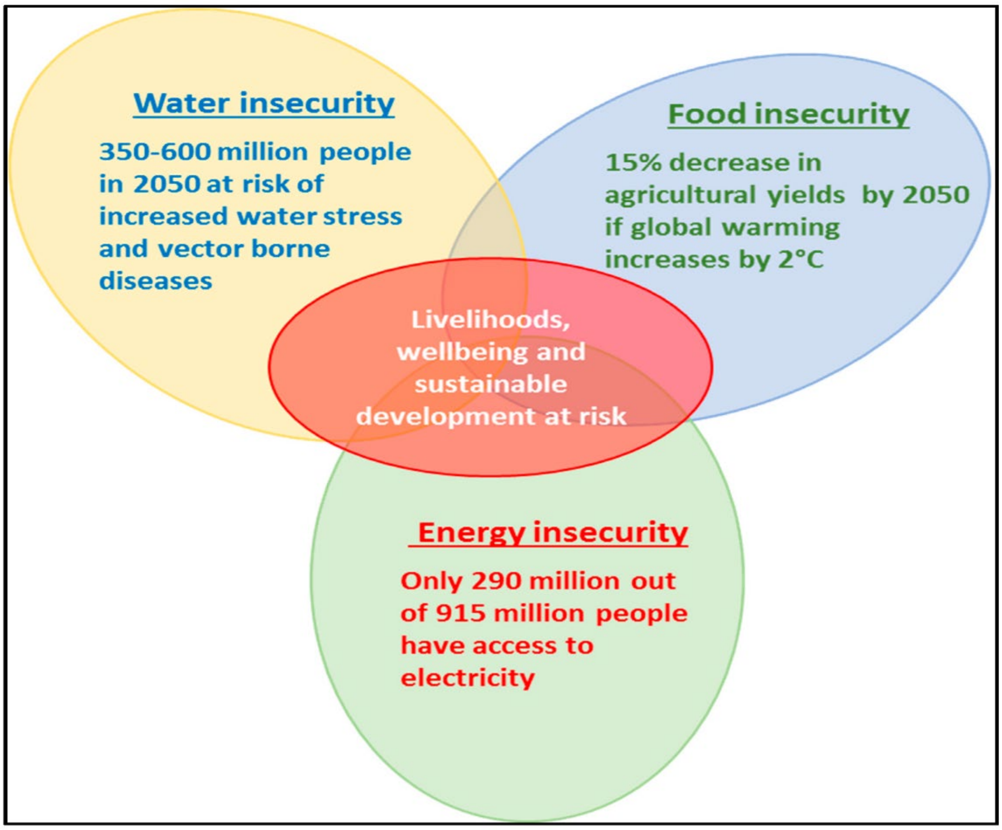

Figure 2.4: Anticipated risks for climate change on WEF resources (Adopted from Mabhaudhi et al., 2019)

Global climate change presents significant challenges at regional levels by increasing temperatures, reducing snowpack, and altering precipitation patterns, which in turn affect the WEF nexus and ecosystem processes (Liu, 2016). Projections indicate rising air temperatures, declining snowpack, unpredictable precipitation, higher evaporation rates, prolonged droughts, and rising sea levels (IPCC Climate Change Synthesis Report, 2014), all of which will put pressure on WEF resources. Reduced rainfall, along with more frequent and intense droughts and floods, is causing drastic shifts in plant habitat distribution, having negative impacts on agriculture and food security. Since over 60% of global food production depends on rain-fed agriculture, lower precipitation levels threaten food production and increase the demand for irrigation water.

Climate change directly impacts food security by influencing crop productivity, yield quality, crop failures, livestock losses, farming costs, and agricultural practices due to shifting weather patterns. Indirectly, it impacts food production by affecting water availability (Carter & Gulati, 2014). Since water is central to the WEF nexus, reduced rainfall will disrupt energy generation and food production, jeopardizing regional stability (Nhamo *et al*., 2016). In Africa, the agricultural sector accounts for over 80% of total freshwater withdrawals, meaning even a slight increase in water demand will significantly impact overall water availability (FAO, 2015). Additionally, changes in wind patterns, cloud cover, and precipitation influence renewable energy generation, particularly hydropower, which is highly susceptible to drier conditions. Rising temperatures will also accelerate evapotranspiration, leading to increased water loss during cooling processes (Chirisa & Bandauko, 2016). Figure 2.5 illustrates how climate change impacts the supply and demand of water and energy, reducing precipitation, groundwater recharge, and streamflow, ultimately impacting water availability and energy production.

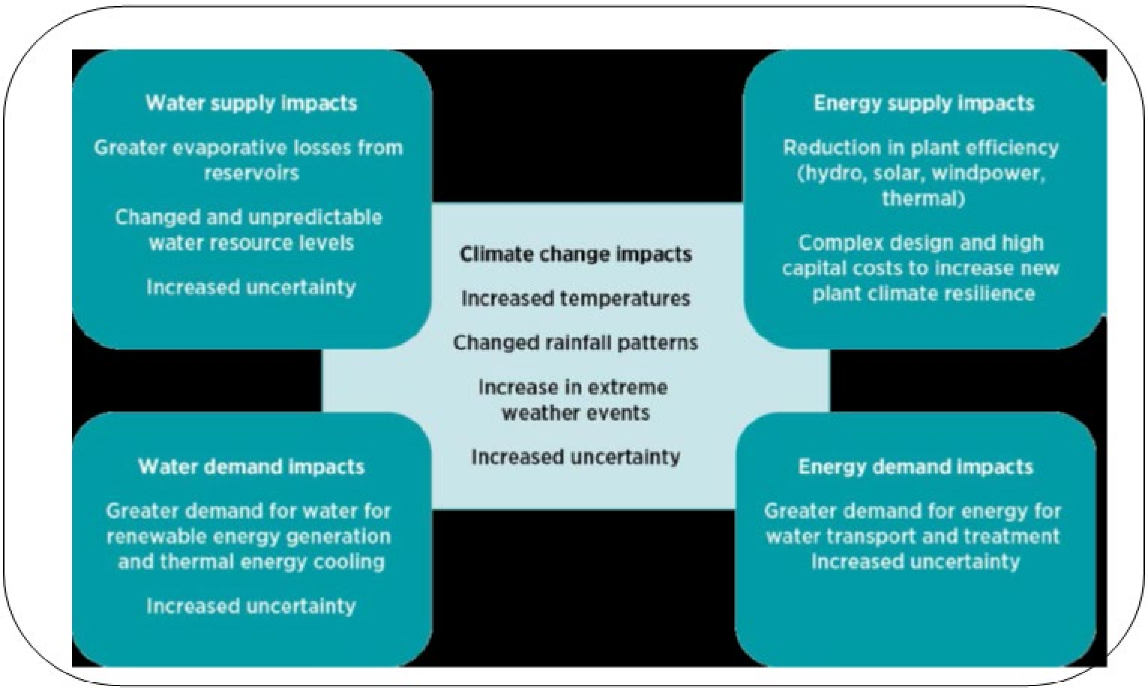

Figure 2.5: Impact of climate change on water-energy-food (Adopted from Bates., 2008)

2.4 WEF nexus and security

2.4.1 Water security

Water security is defined as the ability of a population to ensure that they have sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development. This includes protection from the extreme forces of water and its destructive potential and maintaining an ecosystem in a peaceful and stable environment (UN Water, 2013). This is achieved when water is available for all without the threat of scarcity.

Water security is increasingly crucial for sustainable development in industrial areas (Bichai *et al*., 2018). The sustainable management of water resources and ensuring water security play a vital role in shaping responsible policies that support both ecological and economic stability. Excessive water consumption has led to environmental degradation, such as the depletion of groundwater reserves and the draining of lakes, rivers, and wetlands (Parry *et al*., 2007).

To overcome these challenges, the national government has launched progressive policies and laws related to the water sector, which require harmonization with the constitution in order to be implemented (Madhlopa *et al*., 2014). Various industrial operations, from the extraction, mining, processing, refinement, and disposal of fossil fuels to the production of biofuel feedstock and power generation, use water. Simultaneously, water extraction, transportation, distribution, and treatment require energy. Energy also powers agricultural processes, including land preparation, fertilizer production, irrigation, planting, harvesting, and movement of crops. Production of food also affects the water sector by contributing to land degradation, altering runoff patterns, disrupting groundwater discharge, and influencing water quality and availability for other uses, including natural habitats.

2.4.2 Energy security

Energy security is defined as the continuous accessibility of energy sources at an inexpensive cost (IEA, n.d.). As energy is vital for daily life, ensuring energy security is crucial for all individuals. According to the IEA (2014), energy security encompasses the uninterrupted supply of energy and involves various aspects of the energy economy, including its associated risks and challenges.

In South Africa, coal mining is integral to energy security, with Eskom purchasing nearly half of the domestic coal supply (Chamber of Mines of South Africa, 2018). At present, renewable sources make up only slightly more than 3% of South Africa's electricity generation (FAO, 2016), however costs for these technologies are falling sharply (Walwyn and Brent, 2015). Energy security can be categorized into long-term and short-term aspects. Long term energy security focuses on making necessary investments to ensure a stable energy supply that align with economic and environmental demands, while short-term energy security relates to the ability of the energy system to respond quickly to sudden fluctuations in supply and demand.

Hoff (2011) presented a conceptual framework for the Bonn 2011 Nexus Conference, highlighting the interconnections between water, energy, and food in relation to ecosystem services, urbanization, globalization, security concerns, and dual development goals aimed at reducing poverty and supporting economic growth. Figure 2.6 illustrates the WEF nexus framework, emphasizing the complexity of these interconnections, with water availability as a central factor. It also considers the importance of sustainable development initiatives, governance strategies, innovations, and key principles related to society, the economy, and environmental services.

2.4.4 Food security

According to the Food and Agriculture Organization (FAO), food security is only achieved when all people at all times have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life (FAO, 2006).

Agriculture in South Africa is facing limited arable land and low productivity. While about 30% of the country’s land is classified as rangeland, in areas of low rainfall it is primarily used for game ranching (Milton-Dean, 2011). Only around 14% of the land is suitable for dryland farming, while only 3% is considered high-potential arable land (Collett, 2013).

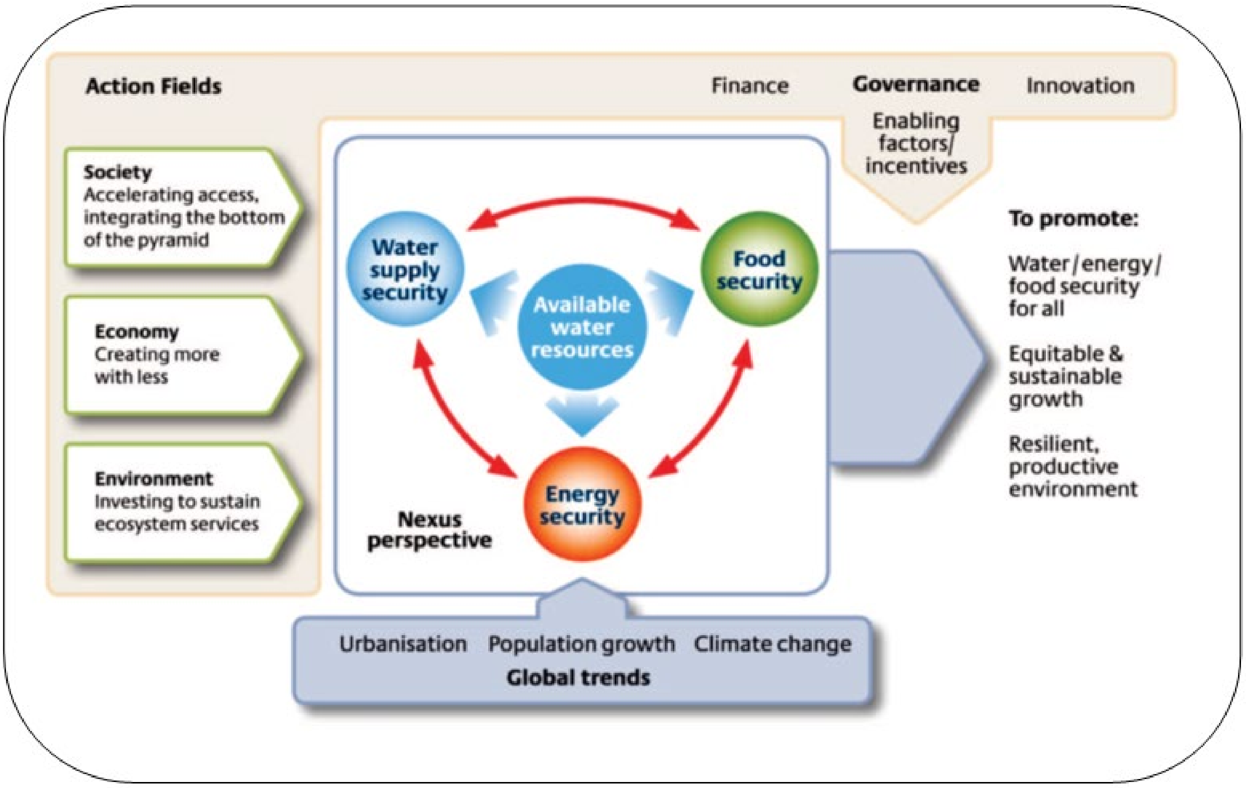

Figure 2.6: WEF security nexus: Adopted from Hoff (2011)

2.4.4 WEF nexus security

Gupta (2017) argued that the WEF nexus is a security nexus for system welfare. An emerging resource security focus that is leveraging the WEF nexus as the guiding framework is based upon the notion that economic growth may soon become constrained by shortages of one or more sectors that comprise this nexus (Salam *et al*., 2017). It addresses an important factor for the sustainability of resources through different areas of global growth, such as the urbanisation of the global population.

Leese and Meisch (2015) argued that while sustainability has traditionally been about distributional justice, today it is increasingly conceptualised in terms of resource security. Leese and Meisch (2015) suggested that the WEF nexus security focus on an entirely technocratic analysis that prioritises the securitisation of issues: in other words, a security agenda based on the risk of non-supply is an economic agenda, not one that engages with the challenges of livelihoods in the traditional debate around sustainable development (Flach *et al*., 2014).

To secure resource WEF nexus security across all people in a sustainable fashion, the quality and quantity of ecosystem services and the resource base are supporting spelling ‘integrity’ which needs to be maintained, while maintaining and consolidating access to resources. Additionally, access to resource management and WEF nexus security should also extend to everyone, even in rural areas like the one in the study area.

2.5 Influence of hydrology on the WEF nexus smart innovation, technologies and practices

The production of both food and energy depends on having an adequate supply of water with appropriate quality. Nevertheless, the Water-Energy-Food (WEF) nexus discussions rarely reflect on water quality relevant to health, environmental, and overall well-being (Varis & Keskinen, 2018). This is particularly critical in Southern Africa, where recent hydrological extremes, such as the multi-year "Day Zero" drought in Cape Town (2015-2018) and ongoing water stress in regions like the Eastern Cape and Limpopo, alongside intense flooding events such as those in KwaZulu-Natal (2022, 2023) and Cyclone Idai's impacts (2019), starkly illustrate the direct and severe impacts of hydrological variability and change on the WEF nexus. Liu *et al*. (2017), Scanlon *et al*. (2017), and Cudennec *et al*. (2018) explain that contributions from hydrological sciences to the resolution of WEF nexus challenges include hydrological tools and models, and integrated socio-hydrological modelling methods (e.g., van Emmerik *et al*., 2014). These are especially pertinent given the increasing unpredictability of hydrological regimes in Southern Africa due to climate change, evidenced by more frequent and intense extreme weather events, which these tools aim to help understand and manage to facilitate practical implementation of the nexus for WEF.

Hydraulic infrastructure such as hydropower dams, can serve multiple purposes such as helping to control floods while simultaneously enhancing water resources for irrigation, energy generation, among other uses (Liu *et al*., 2013; Pech, 2013; Daher & Mohtar, 2018; Mayor *et al*., 2018).This fosters synergy between the WEF sectors, creating mutually beneficial outcomes for both the energy industry and agricultural communities, regardless of their proximity to these infrastructures, although their efficacy can be severely tested during prolonged regional droughts that impact dam levels, as seen with Lake Kariba in recent years (e.g., 2019, 2022-2023).

In certain regions, including the current study area, access to high-quality food and water is fundamental for survival. Therefore, this research aims to illustrate how explicitly incorporating hydrological aspects into the WEF nexus framework strengthens its value for decision-making towards sustainable management of these resources. Hydrological factors are crucial to the WEF nexus, as elements like climate change and water quality can hinder efforts to enhance WEF security. This phenomenon is particularly important for low- and middle-income regions, such as the study area where WEF systems are commonly subject to high impacts from such hydrological stresses (Schlör *et al*., 2018).

2.5.1 The impacts of water quantity on WEF resources

The increasing shortage of water significantly affects energy and food production. As the 29th driest out of 193 countries, South Africa is a water-scarce country with an estimated 1110 m^3 of water available per person (Gulati *et al*., 2012). Furthermore, its rainfall differs significantly in seasons and it is unevenly distributed across the country (Gulati *et al*., 2012). Recent prolonged droughts in provinces like the Eastern Cape and parts of the Northern Cape (e.g., 2019-2023) have further underscored this vulnerability, leading to severe water restrictions, agricultural losses, and heightened competition for scarce resources, bringing numerous challenges for energy, food production, and security. With energy and food requiring a certain quantity of water, low availability, exacerbated by more frequent and intense drought cycles, leads to critical trade-offs in the energy-food and resources sectors.

Energy prices represent a major portion of operational expenses in the water sector, influencing access to water. Approximately two to three percent of global energy utilisation is estimated to be dedicated to pumping and treating water for residential, commercial, and industrial use (Segrave *et al*., 2007). Thus, the less water available, the more energy is required due to the increased need to pump deeper and deeper for groundwater. This trend has been visibly accelerated in drought-stricken areas across Southern Africa, where municipalities and agricultural users have increasingly turned to deeper, often unsustainable, groundwater abstraction as surface sources diminish, a pattern observed during Cape Town's 'Day Zero' scare and in many rural communities in Limpopo and Zimbabwe. Water scarcity also affects energy production as a specific quantity of water is needed to cool thermal power plants. For instance, significantly reduced inflows into major hydropower reservoirs like Lake Kariba have, at various times in recent years (e.g., late 2022 into 2023), curtailed electricity generation for Zambia and Zimbabwe, with knock-on effects for the Southern African Power Pool. Water quantity greatly impacts WEF resources because when water availability is low, energy production is often reduced. Without energy for pumping and water treatment, the transportation of both treated and untreated water becomes difficult, leading to a diminished water supply, thus contributing to low food productivity.

2.5.2 The impact of water quality on energy

Coal mining and power generation consume 5 and 2% of South Africa's water, respectively (DWA, 2013). Water quality influences both energy production and demand. According to Miara *et al*. (2013), water temperature is significant in power generation, as higher temperatures can decrease power plant efficiency and even lead to shutdowns when they near regulatory threshold limits. Water in energy plants is used for cooling; therefore, the water at high temperatures, a condition increasingly likely with rising ambient temperatures and heatwaves linked to climate change, can lead to plant system failure and disruptions. Recent events like the extensive flooding in KwaZulu-Natal in 2022 also demonstrated how high sediment loads and debris in raw water sources following extreme rainfall can disrupt operations at conventional power plants and water treatment facilities supplying them, necessitating temporary shutdowns or reduced output.

In water-dependent power plants, the impacts of low flows and cooling water shortages across the current fleet of thermal affect the productivity of the power plant (Figure 2.7). The requirement for energy production has regional variability based on the quality of water sources and pumping needs. In most power plants found in arid areas, water scarcity often conveys great challenges to achieving the sustainable development of energy security because it may necessitate using lower quality water, such as saline water. Using water of low quality, such as that impacted by Acid Mine Drainage (AMD) prevalent in South Africa's Mpumalanga Highveld coalfields, has an impact on energy production because it requires extensive pre-treatment (like desalination or neutralization) before it can be used, increasing operational costs and energy demand. This challenge is amplified by climate change, where declining rainfall can reduce the dilution capacity of rivers, concentrating pollutants.

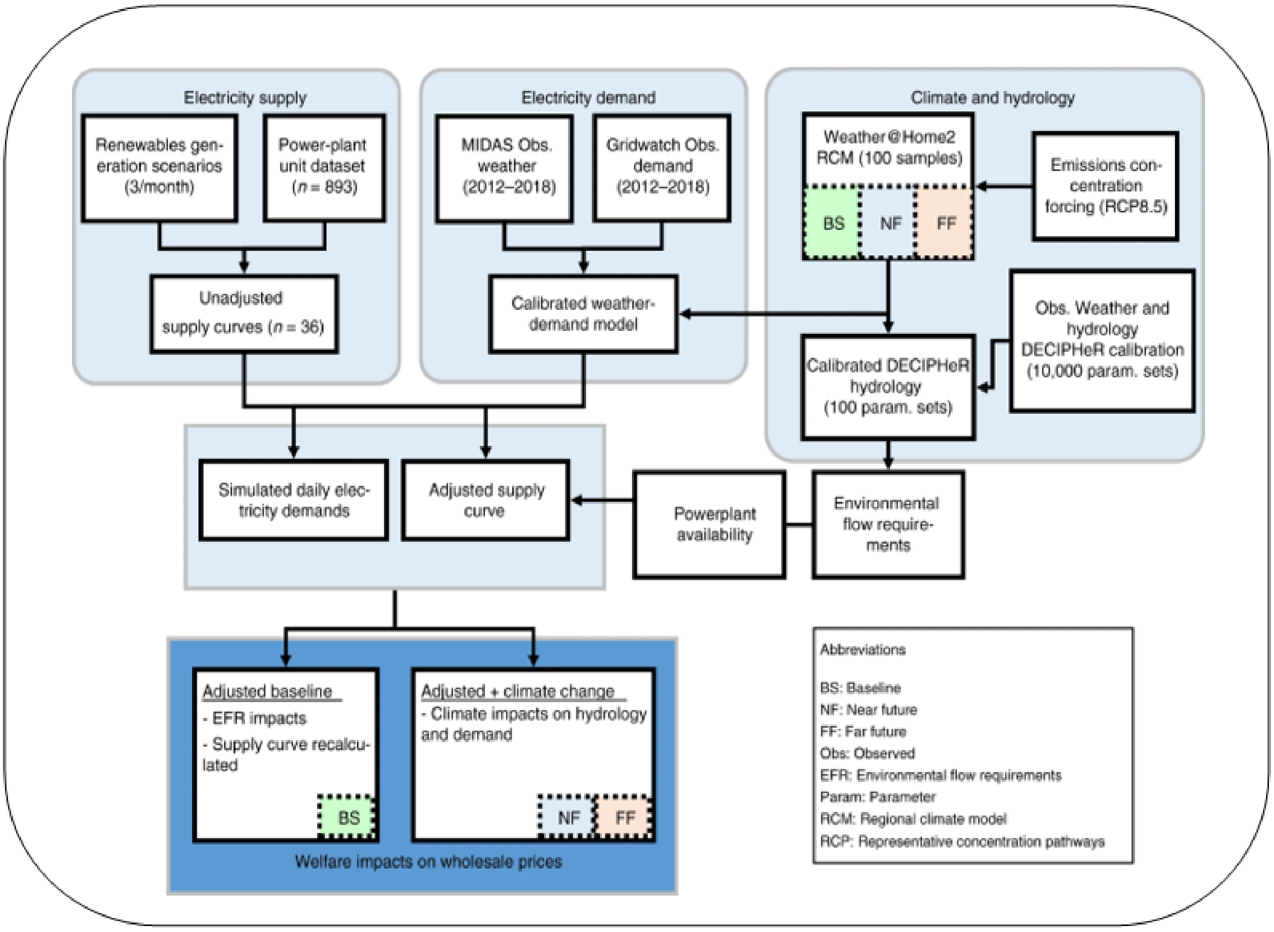

Figure 2.7: A framework combining hydroclimate and electricity supply-demand models (Adopted from Byers et al., 2020)

2.5.3 The impacts of water quality on food

Agriculture relies on a sufficient supply of water with suitable quality. The primary pathway in which water quality impacts food security and quality is through the use of poor-quality water in crop farming, since irrigating with polluted water can reduce crop yields and pose risks to human health. Pathogens can contaminate food plants through contact with polluted irrigation water, which can pose health risks if the plants aren't properly cleaned (Allard *et al*., 2019). Recent cholera outbreaks in parts of Southern Africa (e.g., Malawi, Mozambique, Zambia, and alerts in South Africa post-2023) linked to contaminated water sources highlight the acute risks when compromised water is used for domestic purposes or, inadvertently, in informal irrigation, directly impacting food safety and public health. Poor-quality water can cause slow plant growth, reduce aesthetic appeal, and sometimes even lead to plant death. Additionally, using saline water can harm plant roots, disrupting their ability to absorb water and nutrients. Poor-quality water can cause slow plant growth, reduce aesthetic appeal, and sometimes even lead to plant death. Additionally, using saline water can harm plant roots, disrupting their ability to absorb water and nutrients. Singh (2015) stated that irrigation water quality has been treated as an important environmental parameter in the context of sustainable development in the last few decades; therefore, the indiscriminate use of low-quality irrigation water for crop production has an adverse effect on the environment.

2.5.4 Impact of water quality on the WEF nexus

Due to the rising demand for water in food and energy production, the global water scarcity is expected to worsen. This scarcity results in poorer water quality, as the availability of water has resulted in steadily deteriorating quality of outlets from the country's irrigation systems due to higher salinity and pollutant levels in drainage water (Barnes, 2014). This trend is expected to intensify with climate change, as evidenced by projections of increased aridity in western parts of Southern Africa, potentially leading to greater reliance on irrigation and consequently higher concentrations of pollutants in return flows. The widespread 2022 flooding in KwaZulu-Natal, South Africa, for example, resulted in extensive damage to sanitation and industrial infrastructure, leading to large-scale contamination of rivers and coastal waters with sewage, industrial chemicals, and debris. This severely impacted water availability for all uses and highlighted the acute vulnerability of interconnected WEF systems to rapid water quality degradation following extreme hydrological events.

Water quality can serve as a point of conflict between the different aspects of the Water-Energy-Food (WEF) nexus, both within national drainage basins and across transboundary basins. (Heal *et al*., 2021). Environmental challenges associated with low water quality usually cause other woes of a social and/or economic nature (Ghodsvali *et al*., 2019); thus, water quality greatly impacts the WEF nexus. For instance, the ongoing degradation of critical river systems like the Vaal or Umgeni in South Africa, impacted by a combination of industrial discharge, overwhelmed municipal wastewater treatment works, and agricultural runoff, demonstrates how poor water quality can simultaneously constrain safe water supply for domestic and industrial use (including energy-related industries), limit its suitability for irrigation, and damage ecosystem health. This creates complex conflicts and trade-offs across the WEF nexus that are acutely exacerbated during periods of both drought (concentrating pollutants) and flood (mobilizing and spreading contaminants), thus demonstrating that water quality greatly impacts the WEF nexus.

2.6 The impact of science, technology, and innovations on WEF nexus

The adoption of innovative and suitable technologies can enhance resource efficiency in the WEF sectors, supporting their security and sustainability (AlQuran et al., 2019). Examples of such technological drivers connecting the three nexus components include the integration of renewable energy, increased energy efficiency, advanced precision agriculture, and the recycling of water and reuse of wastewater. Addressing complex issues such as the WEF nexus requires lateral thinking and innovation systems where experimentations and demonstrations of innovation can be initiated, scaled and social participation is encouraged to achieve sustainable resource management.

Technologies and innovative solutions that utilize the WEF Nexus, where all three resources are inputs to one another, increase resource efficiency and expand the natural resource base available, thus improving the sustainability and security of the three resources.

2.7 Impacts of socio-economic factors on WEF resources

Social and economic factors can significantly affect a person's ability to make health choices, afford and manage resources and survive. Kummu *et al*. (2010); Vorosmarty *et al*. (2000); Wada *et al*. (2011) stated that hanging socio-economic conditions can increase local and global water shortage challenges. Aspects such as education, awareness, social capital, occupational status, and housing status are the socio-economic factors that lead to social resilience through water, energy and food. In recent years, 1.1 billion people worldwide have been affected by energy precariousness, and 1 billion people do not have access to clean energy. Meanwhile, 2.8 billion people still consume primary energy from low socio-economic sources such as coal, charcoal, biomass, firewood, crops, straw, and animal dung (Khizar et al., 2020).

Relying on contaminated cooking fuels indoors has serious health consequences, particularly for children and women. Inhouse air contamination resulted in 2.8 million early deaths each year worldwide, with around forty-four percent of the deaths being children and thirty-six percent being women (IEA, 2017). The socio-economic conditions of households hinder their ability to access clean energy, water, and nutritious food

2.8 Technologies, tools and models used in the WEF

Computer models developed included WEF nexus-based data to analyse resource requirements, with potential future challenges and sustainable development. Largely, the new WEF nexus tools were already gaining steam since 2012, following the Bonn Conference on WEF, where the signature nexus approach was introduced, as evidenced by the increasing annual trends and overall cumulative total number over time. The development of WEF nexus tools such as the multi-scale integrated assessment of Society and Ecosystem Metabolism (MuSIASEM) and ANEMI, which existed before 2011, indicates that the WEF nexus concept emerged prior to 2009. The year 2011 marked a key point when the concept gained greater visibility and was incorporated into broader research and policy discussions (Senzanje *et al*., 2022). Since the rise of the WEF nexus, various models and tools, including Windows Event Simulation (WESim), Cyber Learning Environment for Workforce (CLEW), Sankey diagrams, MuSIASEM, WEF Nexus Tool 2.0, and ANEMI, have been developed. Table 2.1 outlines the potential models and indices that can be used to assess the WEF nexus in South Africa.

Table 2.1: Summary of models and indices that could be potentially used to evaluate the WEF nexus in South Africa, adapted from Martinez-Hernandez et al. (2017)

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

Table 2.1 continue…

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

2.8.1 Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM) model

The MuSIASEM is an innovative tool based on Bioeconomic and Complex System Theory, designed to incorporate integrated quantitative data (Giampietro et al., 2013). It draws on concepts such as the flow-fund model, multi-purpose grammar, and impredicative loop analysis. This model facilitates the simultaneous consideration of economic, social, technical, ecological, and demographic factors when analysing the metabolic patterns of modern societies. MuSIASEM was used for simulating the WEF nexus in locations such as the Republic of Mauritius, the Indian State of Punjab, and South Africa, under various scenarios and conditions (Giampietro *et al*., 2013). Despite its complexity, the model effectively analyses the interconnectedness of these three resources, considering factors like population growth, greenhouse gas emissions, and land-use changes at both national and sub-national levels. Rooted in bio-economics, complexity, and hierarchy theory, MuSIASEM enhances sustainability perspectives by depicting social-ecological systems across different hierarchical levels, geographical areas, and timeframes (Madrid-Lopez *et al*., 2021).

2.8.2 An integrated assessment of global change (ANEMI model)

The ANEMI model includes eight coupled subsectors: climate, carbon cycle, economy, land, population, natural hydrological cycle, water use, and water quality systems (Davies, 2007). Each component is represented as a system dynamic model, with feedback links connecting them (Davies and Simonovic, 2010). Providing a structure that allows the model to explicitly capture feedback among the components, making it easy to trace their interconnections. The model was built with Ventana Simulation Environment (Vensim) software, it model enables conceptualization, simulation, analysis, and optimization of system dynamics (Shamsuddoha et al., 2013). Its user-defined causal loop simplifies tracking for further evaluation and analysis. By applying a system dynamics approach, the model effectively represents the linkages within the WEF nexus. Additionally, the ANEMI model improves upon earlier models by incorporating the production of food and improving the optimization of energy economy component (Akhtar *et al*., 2013).

2.8.3 WEF Nexus tool 2.0

According to Mohtar and Daher (2014), the WEF nexus tool calculates key metrics, including water consumption, regional and imported energy use, land and financial requirements, and carbon emissions, based on input data. Wicaksono *et al*. (2017) describe this model as an integrated platform that synthesizes scientific data and identifies potential trade-offs among water, energy, and food resources. It allows users to generate different scenarios by modifying key WEF portfolio inputs, assess resource demand, and compute the sustainability index for each scenario. Developed to support decision-makers, the model aids in identifying sustainable resource management approaches influenced by the WEF nexus, while addressing the challenges it presents. However, a restraint of the model is its application on the specific context of Qatar, requiring information about the study area's characteristics. Despite this, it remains user-friendly and could serve as a foundation for developing other simulation models.

2.8.4 South African Times-Water (SATIM-W) model

The SATIM-W model is a planning tool for the cost-effective and sustainable analysis of the trade-offs in terms of W-E system interactions (Ahjum et al., 2018). It is tailored to South Africa and integrates extensive quantitative data on water supply, consumption, and expenses as well as qualitative information on factors such as water quality and treatment. Ahjum *et al*. (2018) highlighted that the model also incorporates scenarios including climate change impacts, economic growth, local environmental best practices, policy compliance, and the adoption of low-carbon technologies.

2.8.5 Earth Observations for Water, Energy, and Food (EO-WEF) nexus geo-tool

The EO-WEF is a multisectoral information system made for visualizing customizable data and producing time series at any location (Kiala et al., 2022). Earth observations (EOs) provide numerous data sets for the majority of the nexus components at low cost and at different temporal and spatial resolutions. The other factor is the evolution of Cloud Computing, which really allows vast quantities of information to be processed.

This application runs on Google Earth Engine, a cloud solution that stores EO and scientific data automatically updated in real-time over 40 years. Essential nexus variables data are provided by the EO-WEF application, which can be improved by adding other kinds of data not captured by the EOs.

2.9 Mapping and comparing WEF nexus smart technologies, innovations, technologies and practices using GIS

To understand the intricate interlinkages between the energy, water, and food/agriculture subsystems at a local level in developing countries, the bilateral, circular connections between the different system elements need to be mapped systematically (Dienst et al., 2018). Mapping is largely qualitative and is often based on non-measurable information drawn from project reports, scientific literature reviews, or ground-truther fieldwork. While mapping, surveys and observations are used to collect WEF resource data. This approach creates a unified map that offers various advantages, such as integrating individual research findings into maps as cohesive methods for interdisciplinary research, fostering better understanding of WEF resources (Endo et al., 2015). According to Duecker (1979), a Geographic Information System (GIS) is a specific type of information system where the database is made up of observations on spatially distributed features, activities, or events, which can be represented as points, lines, or areas. A GIS processes this data to extract a set of information for analysis. This framework uses location-based data to analyze spatial information, simplifying the study of maps and revealing underlying geographical patterns.

GIS has many different benefits/uses, such as improving strategic decision-making by providing regional and location information. GIS can also help reduce operational costs by boosting and controlling operational tasks and reconfiguring different procedures. Visual map data can help in storytelling and help in understanding situations in a better way. It is also useful in maintaining crucial geographical data and records about different regions' old and new changes. It also benefits the user understanding patterns, relationships, and geographic context is also beneficial to the users as it may help improve communication, efficiency, and management, as well as decision-making.

2.9.1 Different mapping platforms of GIS

There are several definitions of GIS (Goodchild, 2009; Sweeney, 2008; Camara, 2004). GIS is a technological tool that aids in understanding geography and making informed pronouncements, ranging from basics like navigation to more intricate ones, including disaster forecasting and management (ESRI, 2006). The proposed open GIS framework is structured around four main components: open software, open data, open standards, and open education (Sui, 2014). In GIS, data representation must be determined before analysis can take place. GIS data is categorized into two types: spatially referenced data (i.e., location), characterised through vector and raster formats. The second group is a group of attribute data, which is represented in tabular format and/or descriptive data (Tsou, 2011).

(a) ArcGIS

ArcGIS is a platform that enables the management and analysis of geographic information by visualising spatial data through layered maps. Its purpose is to computerize the way of capturing, storing, editing, updating, and analysing data (Khan et al., 2017). ArcGIS is ideal for use by both small and large organisations because it is easier to integrate and targeted toward non-programmers. Figure 2.9 displays the interface of ArcGIS with the Microsoft Office-style ribbon menu at the top, which organizes a vast array of sophisticated tools under intuitive tabs like "Map," "Analysis," and "Edit." The layout is structured for efficiency, featuring a contents panel on the left where users manage the order and properties of all data layers. On the right, the catalogue panel functions as a comprehensive file explorer for all project-related data, from geodatabases to toolboxes. At the centre of this integrated workspace is the main map view, where geographic data is visualized and interacted with, reflecting a powerful, all-in-one system designed for in-depth spatial analysis and cartographic production.

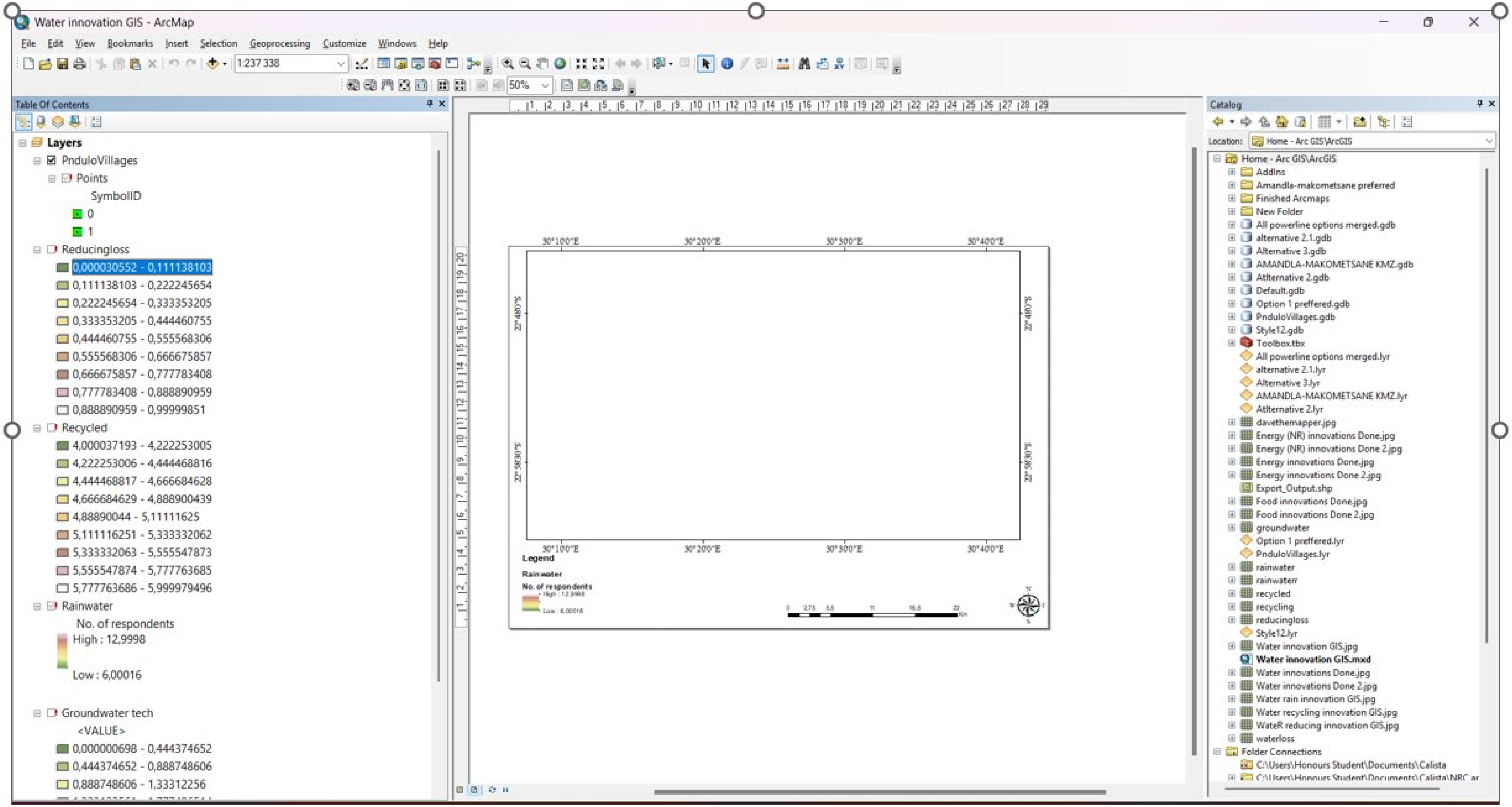

Figure 2.8: A view of the ArcGIS Pro interface, showcasing its layout with a central map display

(b) CARTO

CARTO is an electro-anatomical mapping system that enables three-dimensional anatomical reconstruction of the ventricles in sinus rhythm or pacing, helping to identify areas of scar tissue, anatomical and functional barriers, and slow conduction. This allows for the definition of the substrate for ventricular tachycardia (VT) (Marchlinski *et al*., 2000). The platform is primarily used by scientific, analytical, and development teams to create competitive advantages, optimize business processes, and forecast business outcomes through the use of technology, data, and services offered by CARTO. Additionally, electro-anatomical mapping allows for the three-dimensional localization of ectopic atrial tachycardia (Weiss *et al*., 2001). Figure 2.9 below illustrates the dynamic, web-based interface of CARTO.

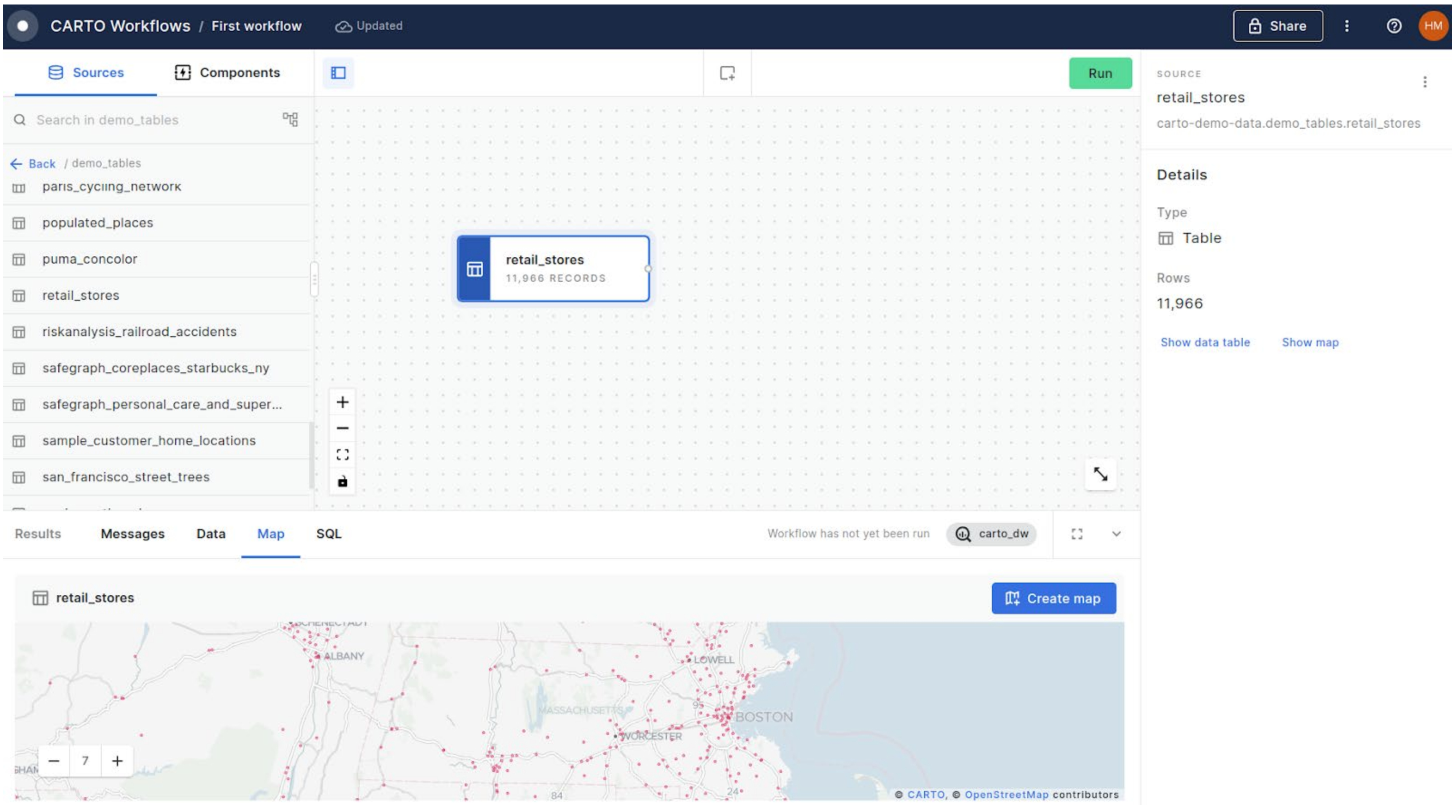

Figure 2.9: Example of a location intelligence dashboard built on the CARTO platform (Source: CARTO, 2024).

(c) Quantum Geographic Information System (QGIS)

QGIS is a powerful tool that enables users to create maps with multiple layers using various map projections, making it an excellent option for spatial data viewing, editing, and analysis. It is an open-source, cross-platform desktop geographic information system application that supports the viewing, editing, printing, and analysis of geospatial data (Vladmir *et al*., 2016). QGIS is also integrated with other open-source GIS packages, such as PostGIS, GRASS (Geographic Resources Analysis Support System), and MapServer, providing users with a broad range of functionalities. Additionally, QGIS can be extended through plugins written in Python or C++, allowing users to customize and automate GIS functions (Tsou, 2011). Ramsey (2007) stated that QGIS supports Digital Elevation Model (DEM), ArcGrid, Earth Resources Data Analysis System (ERDAS), Spatial Data Transfer Standard (SDTS), and Georeferenced Tagged Image File Format (GeoTIFF) raster formats. Figure 2.10 showcases the user interface of QGIS. Its layout represents a classic and highly functional approach to GIS software. A standard menu bar and a customizable set of toolbars at the top provide access to a comprehensive suite of functions for data creation, editing, and analysis. Similar to ArcGIS Pro, it features a layers panel on the left for managing map layers and a browser panel for locating and adding data. The spacious central map canvas is the primary workspace for cartography and data visualization. This interface, known for its flexibility and power, underscores QGIS's role as a versatile and accessible tool for a global community of users, capable of handling complex GIS projects from start to finish.

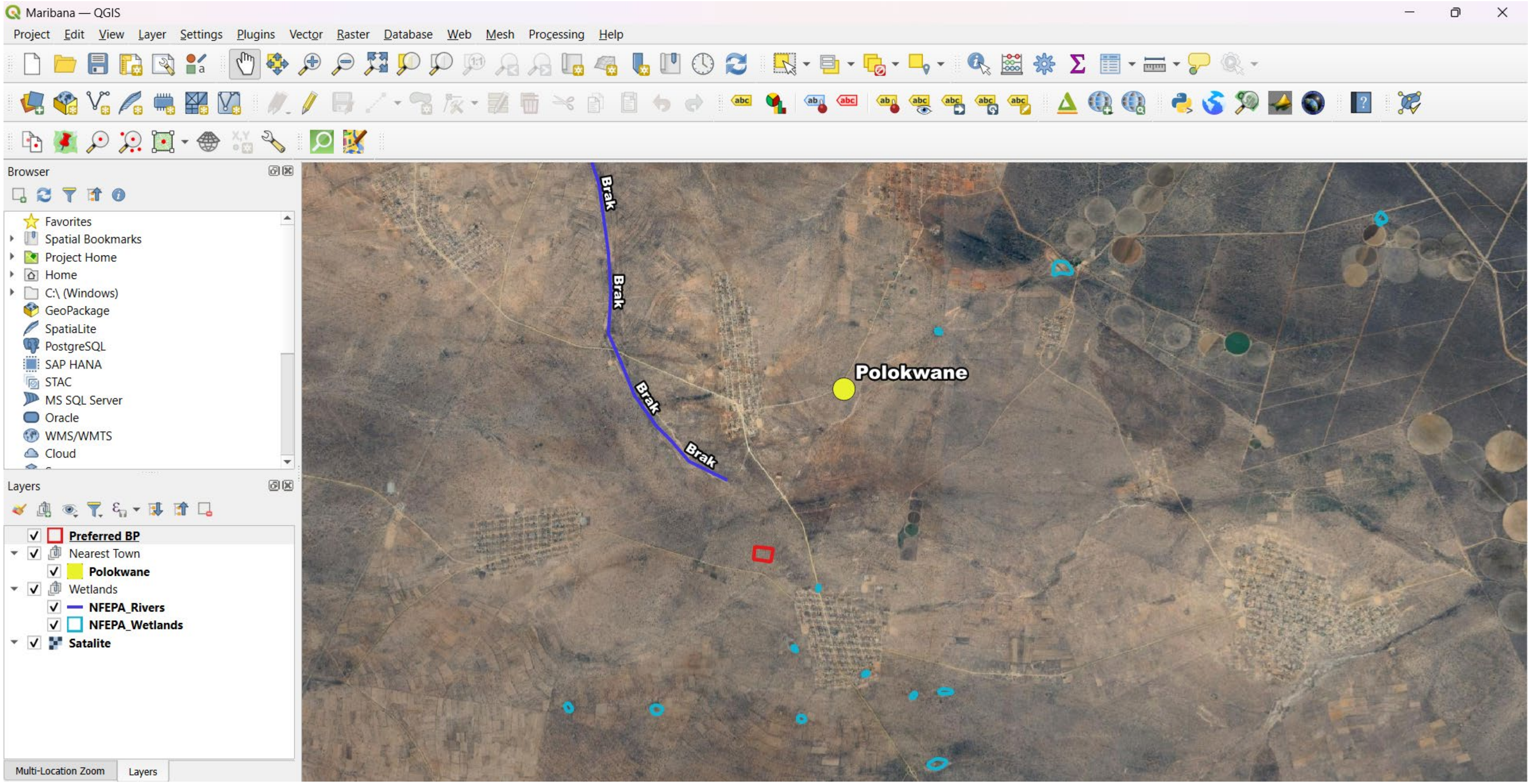

Figure 2.10: The QGIS Desktop environment, displaying a map composition with multiple data layers

2.10 Previous studies

Smajgl *et al*. (2016) analyzed a sectoral balance dynamic WEF nexus framework, considering equal priority sectors in the Mekong Basin River, Thailand. The analysis of the study findings showed that this framework has the benefit of illustrating where and/or how relationships change between sectors as a result of an intervention in one individual sector. Martinez-Hernandez *et al*. (2017) proposed NFT or a tool called "Nexus Simulation System" (NexSym) for Water, Energy, and Food (WEF) integrated resource assessment. This is achieved through integration both within and across WEF sectors (ecosystems and consumption components) that drive interactions in a local system, across the United Kingdom (UK). This framework or tool is primarily intended for analyzing local systems, and it requires a specific set of data as inputs for each locale to make an informative assessment. The study also underscores that "collaboration between researchers and local communities to build datasets consistent with local contexts is critical" to be able to use the tool successfully.

Hussein *et al*. (2017) proposed an integrated model that accounts for WEF interactions at the end-use level at the household scale in Iraq. The model estimates the demand for WEF and the produced amounts of organic waste and wastewater. It is also used for exploring the effects of changes in user behavior, diet, income, family size, and climate on household-level WEF resource use and management.

Mabhaudhi *et al*. (2018) assessed the Water-Energy-Food (WEF) Nexus in South Africa. Their research consisted of a comprehensive literature review on the WEF nexus in the country. Its aim was to give a comprehensive literature overview of past, present, and ongoing work concerning the WEF nexus, with a focus on its present situation, potentials, challenges, and opportunities for integrated WEF planning. The review also tackled both technical and policy dimensions, providing a framework to link the WEF Nexus with the Sustainable Development Goals (SDGs), focusing particularly on SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 7 (affordable and clean energy).

Neupane (2021) observed the evolution of the WEF nexus as a critical pathway for sustainable development in South Africa. This paper describes the emergence of the WEF nexus as a polycentric and transformative framework that integrates societal and environmental challenges across multiple sectors. It has showcased advancements in translating the WEF nexus framework into an analytical decision support tool. According to the study, "nexus-based policy decisions on WEF have the capability of contributing and supporting the livelihoods and sustainable socio-economic development for the global Agenda 2030 on sustainable development."

Senzanje *et al*. (2022) investigated the Water-Energy-Food (WEF) nexus for sustainable resource security. Their examination assembled insights from experts on fundamental concepts, analytical instruments, case studies, and major evolutions on the issue of relevance and promise of the WEF nexus as a transformative and circular approach. The research also provided a detailed overview of the accomplishments made in the process of the implementation of the WEF nexus. It also showcased practical implementation examples of integrated resource management and pathways for sustainable development. Research topics included data availability, modeling tools, index creation, and metrics development and applications over different spatial and temporal scales.

Walker *et al*. (2022) investigated the application of the WEF nexus at a local scale in the Inkomati-Usuthu Catchment in South Africa. This study described the available tools, including input and output requirements, temporal and spatial scales, and potential users. It looked into the types of data necessary for each industry and found local information sources after the scale of datasets needed. It did, however, provide context for how these tools may be used in both the Crocodile and lower Komati River basins to support stakeholder engagement and a better understanding of the scope of the WEF nexus and its economic and policy implications.

The Climate, Land, Energy, and Water systems (CLEWs) framework, pioneered by institutions like KTH and SEI (e.g., Howells *et al*., 2013), has gained traction for integrated national planning. Terrapon-Pfaff *et al*. (2018) reviewed its application, highlighting its utility in developing countries, including African nations like Mauritius and Rwanda, for exploring interlinkages between climate adaptation/mitigation and WEF resource management through linked models. Similarly, the conjoined application of established models like the Water Evaluation and Planning (WEAP) system and the Long-range Energy Alternatives Planning (LEAP) system has been instrumental in many African contexts. Studies in basins such as the Nile, Zambezi, and Volta (Gulati *et al*., 2013 for the Blue Nile; McCartney *et al*., 2018 for the Zambezi) have utilized these tools to quantify WEF trade-offs under diverse climatic and developmental scenarios, informing transboundary water and energy planning.

System Dynamics Modelling (SDM) has also emerged as a powerful approach for capturing the feedback loops and non-linear interactions inherent in WEF systems in Africa. For instance, Salah *et al*. (2021) applied SDM to the Eastern Nile Basin to analyse the nexus under population growth and climate change, demonstrating its capacity to simulate complex system behaviour and test policy interventions. The FAO has also contributed significantly, developing methodologies and supporting nexus assessments in various African regions. For example, their work in the SADC region and specific river basins like the Awash often involves tailored analytical frameworks to identify context-specific challenges and investment opportunities (FAO, 2014; FAO, 2018).

Complementing these integrated modeling platforms, researchers like Nhamo *et al*. (2018) have provided critical reviews of WEF nexus research and implementation with a specific focus on Southern Africa, frequently identifying persistent challenges related to data scarcity, governance fragmentation, and institutional capacity, which can limit the efficacy of even the most sophisticated tools. Simpson and Jewitt (2019) also explored the WEF nexus in Southern Africa, emphasizing the importance of incorporating governance and political economy into nexus analysis, arguing that technical tools alone are insufficient without understanding the power dynamics and institutional contexts that shape resource allocation.

More broadly, efforts to develop WEF nexus indicators and indices are crucial for tracking progress and assessing vulnerabilities. Organizations like the UN Economic Commission for Africa (UNECA) and regional bodies have been involved in discussions around metrics suitable for African contexts, considering data availability and relevance to policy priorities (UNECA, 2020). Furthermore, approaches like Multi-Criteria Decision Analysis (MCDA) are being increasingly explored to integrate diverse stakeholder preferences and qualitative information into WEF nexus decision-making, particularly relevant for addressing complex trade-offs in data-scarce African environments (e.g., Zarghami & Akbariyeh, 2022, though not exclusively African, the methods are applicable).

This expanding array of frameworks, models, and analytical tools, from global platforms adapted for regional use to bespoke local assessments, reflects a growing sophistication in addressing WEF nexus challenges. However, as consistently highlighted by research in Africa (e.g., Martinez-Hernandez et al., 2017; Mabhaudhi *et al*., 2018; Walker *et al*., 2022), the successful application of these instruments hinges on robust, context-specific data, strong stakeholder engagement, and the capacity to integrate findings into policy and practice. The ongoing challenge lies in tailoring these tools to diverse African realities and ensuring they empower sustainable and equitable resource management.

2.11 Chapter summary

This chapter contains interrelated literature smart innovations at the household level, the dynamic of the WEF nexus framework, different impacts on water, energy and food resources and the influence that hydrological processes have on WEF resources. Furthermore, different methods of mapping and analysing the WEF nexus were reviewed.

CHAPTER 3: METHODOLOGY

3.1 Preamble

This chapter outlines the study area and research design, which refers to the overall approach selected to combine various elements of the current study and identify WEF nexus innovations, technologies and practices necessary for sustainable development, that can enable communities to effectively use nexus resources. This chapter explained the methods used for data collection and analysis to achieve the study's objectives. Figure 3.1 indicates the summary of the study methodology.

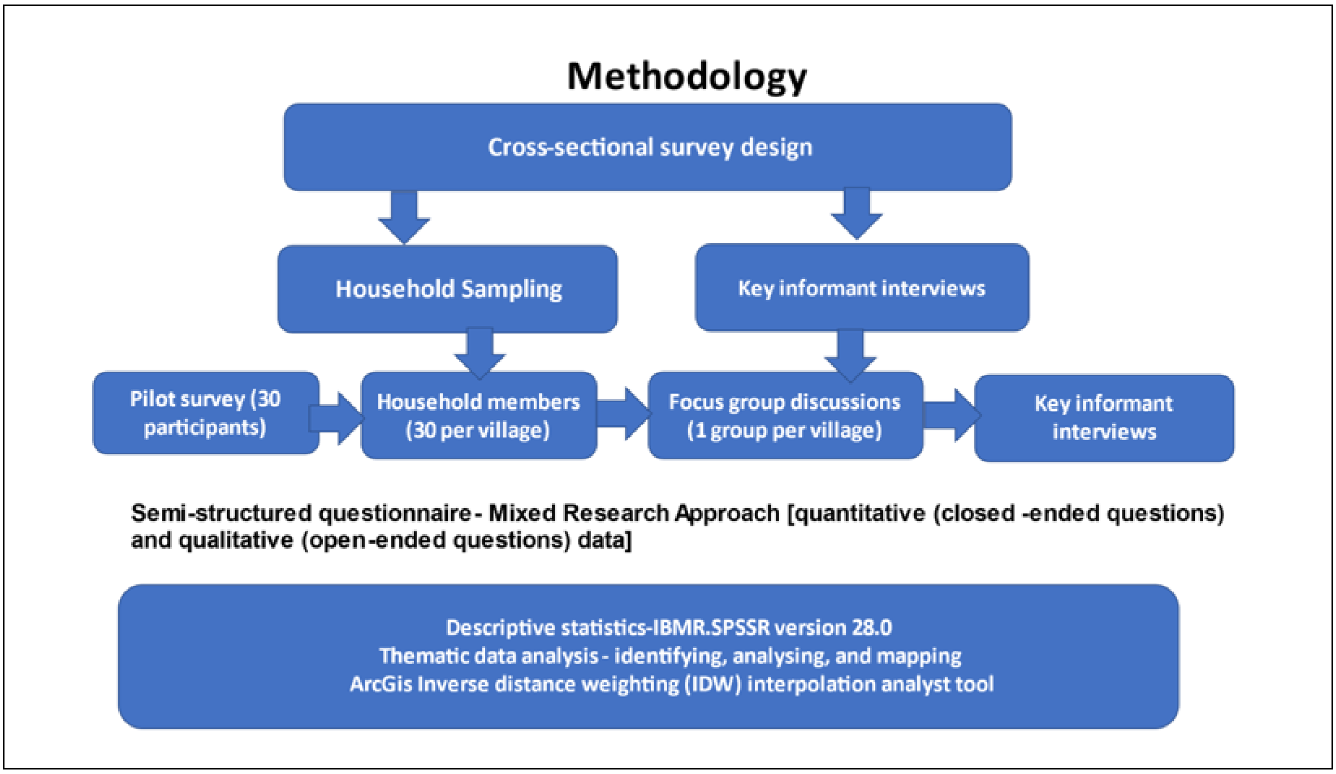

Figure 3.1:Summary of the methodology used in this study

3.2 Research design

Research design is a strategy chosen to organize and manage the entire research process, ensuring it is feasible and addresses the research questions and objectives using reliable research tools (Cohen *et al*., 2018). For assessing the WEF nexus smart innovations, the research design used a combination of both qualitative and quantitative research methods (i.e., mixed method design). The qualitative and quantitative methods include the collection and analysis of data over a particular period (Creswell, 2003). A comprehensive understanding of a research problem and the ability to address research questions should rely on a reliable research methodology (Cohen *et al*., 2018).

The rationale for this methodological integration is deeply rooted in the inherent complexity and multi-dimensional nature of the WEF nexus itself. Relying on a singular methodological approach would invariably yield only a partial and incomplete understanding. The strategic collection and concurrent analysis of both quantitative and qualitative data allows for the triangulation of findings, significantly enhancing the overall validity and reliability of the research conclusions. This integrated design empowers the research to not only describe and measure the phenomena under investigation but also to explain and deeply understand the complex realities of WEF interactions and interventions within the study area, thereby more effectively supporting the overarching goal of promoting sustainable resource management.

The use of two methods further provides an essential broad overview of what innovations are present, where they are located, and their measurable characteristics or impacts. However, while quantitative data can illuminate these aspects, it often falls short of fully explaining why certain innovations are adopted, adapted, or perhaps rejected within specific communities, or how these innovations are integrated into local livelihood strategies.

3.2.1 Qualitative research approach

The exploratory, descriptive, narrative, and analytical components of qualitative research work together, helping to reduce the biases and prejudices of both the researcher and the participants to some degree (Johnson & Onwuegbuzie, 2007; Halcomb & Hickman, 2015; McCusker & Gunaydin, 2015; McKim, 2017). The data and information were collected using questionnaire surveys, and observations were conducted non-numerically. Responses were analysed in tables to obtain the statistical results.

3.2.2 Quantitative research approach

Quantitative research sets out to gather data using measurement to determine trends, relationships, and verify the measurements made (Watson, 2015). The principles applied in quantitative research are the breakdown of sample population selection in an unbiased random manner, the standardized questionnaire/intervention they were provided, as well as the statistical methods (Muhammad et al., 2023). This quantitative methodology ultimately aimed to compare the WEF nexus building in the study area, in order to identify patterns and relations. Similar to the nexus approach, this paper provides a holistic view of the broader context; however, these correlations would be subject to regional specific factors.

3.3 Data collection and procedures

The systematic process of determining and collecting data according to the study design and measurement methodology is called data collection (Ravhura, 2019; Voleti, 2019). Structured and semi-structured questionnaires were used to solicit information from the participants. The questionnaire consisted of closed and open-ended questions.

3.3.1 Sampling methods procedure

Structured questions were employed for the quantitative approach, while semi-structured questions were used for the qualitative approach, each serving distinct purposes in data collection. This approach was aimed at triangulating the findings within the study area. The semi-structured, open-ended questionnaire in the study focused on asking questions like why and how. This was conducted for the purpose of thematic mapping and to gather information for addressing the following issues/themes on assessing and mapping WEF nexus smart innovations:

- Innovations being used;
- Reasons for using such innovations.
- How such innovations are being used, and
- Challenges

Structured, closed-ended questionnaire was used to gather information from the participants to address the following issues:

- The demographic background of the respondents.
- Sources of water.
- Energy use.
- Crops and livestock.
- Marketing channels; and
- Perception of water, energy and food use

3.3.2 Sampling sites

The sampling sites were selected looking at the upper, middle and lower courses of both the Nzhelele and Luvuvhu River Catchments Areas. Six (6) villages, of which are in 3 different profiles of the river, were sampled; due to the unavailability of the village chief and the authorisation from community leaders at Tshakhuma village, only five (5) among six (6) villages were pre-tested during the pilot survey. The village code, name, coordinates, and name of the catchment area each village falls under, as well as the number of samples collected per village, are shown in Table 3.1. The selection of villages was determined by looking at the lower, middle and upper course of the Luvuvhu and the Nzhelele River Catchment Area to determine how different locations around the rivers affect access, use and availability of WEF.

Table 3.1: Sampled villages and their coordinates.

Code	Village	Catchment	Coordinates
SL	Siloam	Nzhelele	-22.92 S 30.30 E
KH	Khalavha	Nzhelele	-22.92 S 30.20 E
PH	Phadzima	Nzhelele	-22.94 S 30.21 E
SM	Sambandou	Luvuvhu	-22.70 S 30.70 E
ML	Malavuwe	Luvuvhu	-22.90 S 30.70 E
TH	Tshakhuma	Luvuvhu	23.04 S 30.30E
Total	6		

3.3.2.1 Sampling size

Population size was determined according to (Fisher *et al.,* 1983) which is as follows:

$$n = Z^2 \left[\frac{pq}{d^2}\right] \quad (1)$$

where *n* is the desired sample size, Z is the standard normal deviate at 95% confidence level (1.96), P as the proportion of the target population estimated to have the characteristic under study (10% or 0.1), q represents the percentage of the target population that lacks the characteristic (1 − p = 90% or 0.9), while d refers to the precision level associated with a statistical significance of 0.05 (or 5%).

By substituting for the values:

$$n = Z^2 \left[\frac{pq}{d^2}\right] = 1.96^2 \left[\frac{(0.1)(0.9)}{0.05^2}\right] = 138.28 \text{ households}$$

However, the study relied on the fast and frugal heuristic approach as suggested by Hafenbradl *et al*. (2016) for the actual sampling and sample size determination. Considering potential non-responses, 180 households were initially targeted, but only an overall of 98 respondents were available for interviews due to different challenges.

3.3.3 Questionnaire survey

The questionnaires (Appendix A) targeted rural communities along the Nzhelele and Luvuvhu River Catchment Areas in Limpopo Province, Vhembe District Municipality, with low-income households and smallholder farmers. The Luvuvhu and Nzhelele Catchment Areas were divided into the upper, middle, and lower areas. The questionnaires paid specific attention to the relationship that exists between WEFs because their degradation significantly affects the socio-economic conditions of people in the study area. The questionnaire survey used in this study included both closed and open-ended questions. Closed questions offered a set of predefined answer options, and respondents were asked to select the most appropriate one. These types of questions are helpful for collecting data and ensuring consistency in responses. Open-ended questions, on the other hand, gave respondents the freedom to provide more detailed and personalized answers in their own words.

The questionnaire was divided into four sections, which are the interview details (designed to gather information about the study respondents); the household typology (which allowed a better understanding of the respondents' background characteristics); and the WEF nexus typology (which was based on characterising the water, energy, and food nexus elements) (Appendix A). The fourth section was based on WEF technological innovations and practices and each household's access to and their consumption of food and water resources. Questionnaires were first written in English to ensure that the villagers understood what was required and then translated into Tshivenda during the survey. It was critical to translate the language to communicate effectively with the respondents. The researcher and research assistants then translated the Tshivenda versions of the responses back into English. This was achieved by conducting a mix of one-on-one, in-person, and phone interviews with different participant groups. Data gathered from household surveys was cross-checked using focus group discussions (FGDs) and key informant interviews (KIIs). Throughout the questionnaire process, the field procedures, protocols, and regulations specific to each village were adhered to.

a) Pilot Survey

Following Walliman (2011), the questionnaires were pre-tested with a total of 40 respondents from the five villages in the study area. This was essential to ensure the questions were clear and could be accurately translated. This was to ensure that no mistakes were made during the questionnaire administration and to avoid uncertainty for the questions. The pre-testing revealed that there was a need to rephrase some of the questions, and a few mistakes and repetitions of questions were recognised. According to Neuman (2014), the researcher and seven research assistants conducted face-to-face interviews with the participants. The average duration of an interview during the pilot survey was 2 hours to 2H30 minutes. Overall, a total of 40 questionnaires were administered: Siloam (5); Khalavha (18); Phadzima (6), Malavuwe (5) and Sambandou (6) from the 9th of July to the 21st of July 2022, surveying only 40 households due to the availability and willingness of respondents to participate in the pilot survey as this survey is not compulsory and respondents had to give out the consent. Table 3.2 shows the number of villages sampled for the pilot survey and the number of samples per village.

Table 3.2: Villages surveyed for piloting and the number of samples per village.

Village	Catchment	No of samples
Siloam	Nzhelele	5
Khalavha	Nzhelele	18
Phadzima	Nzhelele	6
Malavuwe	Luvuvhu	5
Sambandou	Luvuvhu	6
		40

Pictures were taken during the pilot survey while the researcher and research assistants were busy administering the questionnaire. This was done with the respondents' consent as it was first explained to them, and consent was granted. Figure 3.2 displays the pictures taken at Siloam, Sambandou, Phadzima, Malavuwe and Khalavha.

Figure 3.2: Pilot survey participants from five villages that were surveyed.

b) Main Household survey

A random questionnaire survey was used to select thirty (30) households per village to participate, wherein only one adult member over 18 years was interviewed (Kothari, 2004) as a representative of the entire household. The researcher alongside 10 research assistants interviewed the participants face-to-face using Tshivenda language to ensure that respondents understood the questions for proper responses.

The number of research assistants was increased due to the number of surveys administered for the main questionnaire survey. The average duration during the main survey was 1 hour or less due to the changes made to the questionnaires during pre-testing and getting used to the questions by research assistants. Overall, a total of 93 questionnaires were administered: Siloam (13); Khalavha (19); Phadzima (14); Malavuwe (9), Sambandou (18) and Tshakhuma (20), which is shown in Table 3.3.

Table 3.3: Villages surveyed for the main household survey and the number of samples per village.

Village	Catchment	No of samples
Siloam	Nzhelele	13
Khalavha	Nzhelele	19
Phadzima	Nzhelele	14
Malavuwe	Luvuvhu	9
Sambandou	Luvuvhu	18
Tshakhuma	Luvuvhu	20
Total		93

As shown in Figure 3.3, some of the pictures were also taken during the main household questionnaire survey. Four of the six villages shown in Figure 3.3 are Khalavha, Siloam, Tshakhuma and Malavuwe. Although consent was granted in the other two villages, pictures were not taken.

Figure 3.3: Main household participants from all six villages that were surveyed

3.3.4 Focus group discussions (FGDs)

The FGDs were conducted using an interview guide specifically made for these interviews. This approach was used to obtain data from respondents purposely selected as it allows a researcher to select participants based on specific criteria such as characteristics, experiences, or expertise. Purposive sampling can ensure that the sample meets those criteria. In this study, there was one FGD group per village composed of community leaders with similar/common duties and experiences within the community. Thus, a group of community leaders were selected, including community councillors, civic members and chiefs; therefore, overall, a total number of six (6) groups were interviewed. Based on the structured questions, the research team started with a brief explanation of the technique/method for all people present during the FGDs. The number of people per group ranged from (6- 20) participants, and the FGD interview lasted about 2-3 hours. Figure 3.4 shows some images taken during the FGD interview at Khalavha, Siloam, Phadzima and Sambandou, where people were gathered and asked questions collectively.

Figure 3.4: Focus Group Discussion

3.3.5 Key Informant Interviews (KII)

Key Informant Interviews (KII) aim to gather detailed insights from individuals who are recognized as experts or well-informed on a specific topic (William & Luloff, 2006). As noted by Brody et al. (2003), KII not only aids in collecting culturally relevant, localized information but also fosters local collaboration, supporting further research, planning, and change initiatives when local insights are considered and applied.

An interview guide was collaboratively prepared and participants were reached via phone or email. The interviews which were semi-structured took place between October and November 2022. They were conducted in both English and Tshivenda by the researcher and two research assistants. Interviews were done with participants from different fields who all had access to the communities at large. A total number of 6 KIIs were done including the Limpopo Department of Agriculture and Land Reform (Vhembe), Department of Water and Sanitation (DWS), Univen FM, Phalaphala FM, Eskom and Vhembe District Municipality. Table 3.4 shows key informants who were interviewed and their knowledge of WEF nexus. The KIIs are presented by broad categorisation which was made according to their social-institution responsibilities, roles, influence and decision capacity. People from different institutions or organisations were selected because they have first-hand knowledge about these communities and the issues and problems they face regarding water, energy, food or all the nexuses. Two different kinds of questionnaire tools were made; one was specially designed for those in the information and communication sectors.

Table 3.4: Resulting typology and number of engaged key informants.

General category	Type of institution or organisation	Nexus knowledge area
Media	Phalaphala FM Univen FM	All All
Water management Organizations	DWS Water affairs	Water Water
Agricultural organization	Vhembe Department of Agriculture and Land Reform	Environmental practices Agricultural practices
Energy resource organization	Electricity Supply Commission (ESKOM)	Energy
Research and Development (R & D) Organizations	Vhembe District Municipality University of Venda	All Environmental Sc Botany and zoology

The questions asked were related to the themes they advance in relation to water, energy, food, sustainability and holistic programs in relation to the relationship between WEF and the programs that influence individuals and society to act on environmental issues and how they interact with communities. The second set of questionnaires was designed for institutions, wherein community engaging plans, coordination mechanisms with other sectors, communication channels, extensions on WEF technologies, factors influencing the adaptation of smart WEF technologies and what they suggest on WEF nexus solutions were determined. Some of the interviews were done telephonically, while some were done one-on-one. Figure 3.5 shows pictures taken during KIIs at Univen FM, the Department of Agriculture, Land Reform, and Eskom.

Figure 3.5: Key informant's interviews

3.3.6 Limitations and challenges in the sampling process

A general limitation experienced across all study sites was the unavailability of some targeted participants at the time of the researchers' visits. This was often due to residents being away for personal reasons, agricultural activities that required their presence elsewhere, or other commitments.

A more specific and significant challenge arose in Siloam Village, where an unexpected community strike occurred during the planned sampling period. This event led to a temporary suspension of all fieldwork activities in Siloam for safety and ethical reasons, causing a notable delay in the data collection schedule for that particular village and requiring a sensitive rescheduling of research activities once the situation stabilized.

Furthermore, the pilot survey process faced an impediment in Tshakhuma village. The initial plan to conduct the pilot survey in Tshakhuma was not successful due to the unavailability of the village chief during the designated period and consequent delays in obtaining the necessary community leader authorizations specifically for this preliminary testing phase. While the pilot survey was successfully conducted in other selected villages to refine data collection instruments and logistical approaches, the inability to pilot in Tshakhuma meant that the main data collection commenced in that village without the site-specific insights typically gained from such preparatory work. This required careful attention and flexibility during the initial stages of the main survey in Tshakhuma.

These encountered limitations and challenges primarily impacted the research timeline and required adaptive field management strategies. While every effort was made to mitigate their effects on the overall quality and representativeness of the sample, they highlight the dynamic and often unpredictable nature of conducting research within community contexts.

3.4 Data analysis

3.4.1 Analysis of the questionnaire survey responses

The identified WEF nexus smart technologies, innovations, and practices were analysed using the descriptive statistics analysis method. The study objectives were analysed specifically using frequency analysis, which is one type of descriptive analysis. Multiple response analysis was also used, as it allowed the set of responses to be combined and collectively analysed.

Data analysis was also conducted using IBM SPSS statistical software version 29 for the Windows package. Results are presented as Tables and Charts. All responses were manually coded before being entered into SPSS software. For open-ended questions, codes were created by grouping responses with similarities from the surveys into one classification. This aided in generating frequencies of up to 100% from the questionnaire responses.

3.4.2 Mapping and comparisons of WEF smart technologies, innovation and practices

Mapping was grounded on the analysis of fieldwork data. Information from questionnaire surveys and observations on WEF resources were used in GIS mapping. Individual household research findings about the type of innovations used at the household level were incorporated into maps as integrated systems for a cross-disciplinary research approach to enhance shared understanding among the three resources. The results of smart innovation, technologies and practices recorded on SPSS were exported into Microsoft Excel and then into ArcGIS (ArcMap 10.3) to create Inverse Distance Weighting (IDW) interpolation maps that were used to compare the differences/similarities of smart innovation, technologies and practices used in these villages. Four maps were created showing the differences and similarities in innovations being used in the study area.

The ArcGIS (ArcMap) 10.3 platform was used to map and compare nexus smart innovations, technologies and practices. Maps were generated using Inverse Distance Weighting (IDW), wherein location points were generated from Google Earth. Four maps were generated, each with different layers depending on the type of innovations, technologies and practices.

IDW was purposefully selected as the interpolation method due to a careful consideration of its advantages in relation to the specific characteristics of the data and the research objectives. IDW is a deterministic interpolation method based on Tobler's First Law of Geography, which posits that near things are more related than distant things. The method's principle, first formalized by Shepard (1968), assumes that the value at an unsampled location can be estimated as a weighted average of known data points, where the weight is an inverse function of the distance from the prediction location. Its primary strengths, as noted by Li and Heap (2008) in their review of interpolation methods, are its simplicity, speed of computation, and intuitive nature. Unlike geostatistical methods such as Kriging, IDW does not require the user to make complex assumptions about the underlying statistical distribution of the data or to engage in the often subjective and time-consuming process of variogram modelling.

At its core, IDW operates on the highly intuitive principle that points closer to a prediction location have a greater influence on the estimated value than those farther away, a concept that directly reflects Tobler's First Law of Geography. This deterministic approach assumes that the phenomenon being modeled is driven primarily by local variations, making it particularly suitable for creating clear visualizations based on proximity.

One of the most significant practical advantages of IDW, leading to its selection over more complex geostatistical methods like Kriging, is its simplicity and less stringent data requirements. Kriging, while often considered more statistically robust as it provides an estimate of prediction error, necessitates a complex, time-consuming, and potentially subjective process of variogram modeling to quantify the spatial autocorrelation of the data. This process not only demands considerable expertise but also relies on statistical assumptions and a dataset that is sufficiently dense and well-distributed to be reliable. In contrast, IDW bypasses the need for variogram modeling entirely, offering a more direct and computationally efficient pathway to interpolation, which is especially valuable when data may be sparse or when rapid exploratory analysis is a priority.

Further comparison to other methods of interpolation, IDW presents a distinct advantage in preventing the generation of unrealistic data values. Spline interpolation fits a mathematical function to create a smooth surface, but in doing so, it can produce estimated values that fall outside the range of the original measured data, creating artificial peaks and pits. Because IDW calculates values as a weighted average of surrounding points, it ensures that the resulting interpolated values remain within the observed data range. This constraint, along with its function as an exact interpolator that honours the original data points, often provides a more plausible representation for many types of environmental and socio-economic data.

The decision to utilize IDW was a realistic one in order to balance the need for a clear and methodologically transparent representation of spatial patterns with the practicalities of the available data. It provided a robust and suitable method for achieving the specific objectives of the spatial analysis undertaken in this research. However, the application of IDW is not without limitations. A primary critique, discussed in foundational geostatistical texts like Isaaks and Srivastava (1989), is its tendency to produce a bull's-eye effect, creating concentric circles of equal value around data points, which may not realistically represent the continuous nature of a phenomenon. Furthermore, IDW is an exact interpolator but cannot generate estimates outside the range of the sampled data; it can never predict a value higher than the maximum observed value or lower than the minimum. This can be a limitation in areas where peaks or troughs are known to exist but were not sampled. Lastly, and critically, IDW does not provide an estimate of prediction error, a key advantage offered by Kriging that allows for an assessment of the confidence in the interpolated surface

3.4.3 Focus group discussion (FGD’s) and Key informant interviews (KII)

The researcher used a triangulation approach to validate and enrich the findings from household-level surveys by combining them with qualitative data from FGDs and KIIs. The combination of multiple methods to study the same phenomenon is most often designated as triangulation (Loiselle *et al*. 2007). Focus groups gather interaction data from group discussions to uncover context-dependent perspectives (Hollander, 2004). This helps researchers understand the dynamics that influence opinions within a social context. In this study, both key informant interviews and FGD’s were conducted with diverse experts and a selected group among each village to obtain a broad perspective on the WEF nexus topic. The data gathered during the KII and FGD was used to achieve a more comprehensive understanding of the WEF nexus smart innovation and practices in the rural areas. The primary goal of using these methods was to use the interaction-based information resulting from discussions and interviews among participants to gain multiple perspectives and validation of data while analysing the household questionnaire survey to test validity through the convergence of information from different sources.

3.5 Ethical consideration

Ethical guidelines were strictly adhered to, and approval was secured prior to the field visit. Lupele (2002) highlighted the importance of seeking consent from traditional leaders or authorities before conducting research in their rural communities. The community chiefs and their counsellors around the Nzhelele and Luvuvhu River

Catchment Areas were informed for permission. The study's objective was thoroughly communicated to the community leaders who assisted in promoting the research among residents to ensure their full cooperation as well as to the participants themselves.

Consent forms (Appendix G) were distributed, clearly outlining participants' rights and emphasizing that this was solely an academic endeavour. Additionally, participants were informed of their right to withdraw from the study at any time if they chose to do so. Data collected from the respondents was treated confidentially. All identifiable information was anonymized during data processing, and each respondent was assigned a unique code to protect their identity, and digital data were securely stored on encrypted drives with restricted access, following the University of Venda's data management policies. Physical documents were stored in locked cabinets within a secured research office. For the purpose of this research, data collection was conducted in accordance with the ethical guidelines and approval provided by the WRC project (Appendix F1), ensuring that all procedures adhered to established ethical standards. Subsequently, additional ethical clearance specific to this study was obtained from the University of Venda Ethics Department (Appendix F2).

3.6 Chapter summary

This chapter described the processes and procedures followed in this study and provides a detailed background on the methodology used, including the research design and methods, data collection, data analysis, and ethical considerations.

CHAPTER 4: WEF NEXUS SMART TECHNOLOGIES, INNOVATIONS, AND PRACTICES STUDY RESULTS

This chapter presented and discussed results on the identification of WEF nexus smart innovations, technologies and practices in Siloam, Khalavha, Phadzima, Malavuwe, Tshakhuma and Sambandou. The chapter comprised the results of the questionnaire survey. It also includes the demographic characteristics used to develop a theoretical understanding of how village members understand the concept of WEF nexus and get their views and opinions on using and managing these resources.

4.1 Demographic characteristics and their relationship with innovation, technologies and practices

This study showed that out of all 93 people interviewed during the main questionnaire survey, only 43 were females, 47 were males, and 3 cases of the respondents were found missing. Many of the respondents were of age above 31 years, with a minor count of those aged 30 years and below, as shown in Table 4.1. About 54.8% (n= 51) people were unemployed, with 11.8% (n= 11) and 20.4% (n= 19) of the respondents working in formal and informal employment, respectively and only 7.5% (n= 7) of the respondents were found to be retired. Table 4.1 also shows that most of the respondents in the study area have a secondary educational level, and only 3.2% (n= 3) furthered their education to university level.

Table 4.1: Respondents' gender, age, education and employment status in the study area (In percentage).

Categories	Respondent type	Frequency	Percentage (%)
Gender	Female	43	46.2
	Male	47	50.5
	Missing	3	3.2
Age	Under 20yrs	2	2.2
	21-30yrs	7	7.5
	31-40yrs	18	19.4
	41-50yrs	19	20.4
	51-60yrs	20	21.5
	Above 60yrs	24	25.8
Education	No schooling	6	6.5
	Primary	13	14.0
	Secondary	55	59.1
	TVET/College	13	14.0
	University	3	3.2
Employment status	Formal employment	11	11.8
	Informal employment	19	20.4
	Unemployed	51	54.8
	Retired	7	7.5
N			**93**

Rainwater was the most used source of water in the study area, with most women (34.4%) and those with unemployed status (36.6%) relying on it for household uses (Table 4.2). A higher proportion of those that have primary and TVET/College education levels also depend on rainwater compared to those with a university education. It was also noted that groundwater was mostly used by a higher percentage of males (6.5%) and those with formal employment (4.3%). This is because those with formal employment have stable salaries and can afford to drill boreholes in their households. A minor percentage of females (1.1%) also use groundwater for household purposes. The focus group discussions and key informant interviews revealed that many rural areas under the study area in the Vhembe District Municipality face significant challenges in accessing municipal water, a problem that has been widely reported across the interviewed radio stations. Communities frequently call for assistance to address ongoing water shortages, highlighting a critical and systemic issue affecting daily life. his reliance on rainwater as a primary source reflects the systemic inadequacies in municipal water supply and the community's adaptation to these ongoing challenges.

The study showed that water recycling is mostly used by 19.4% of respondents with secondary education, 15.1% unemployed than it is by those with university education (1.1%), formal employment (4.3%) and those who are retired (1.1%). This is because most people do not have access to enough water in their households. In addition, reducing water loss is the least used technology in the study areas, with only 2 people practising it. This was because people did not know how to practice water loss reduction to save water; therefore, educational awareness is required.

In Table 4.2, it is shown that conservation agriculture (CA) is the most used innovation in food innovations, technologies, and practices, with 19.5% males and 22.6% females. The study also revealed that CA is mostly used by those with secondary education (25.8%) and those who are unemployed (23.6%) compared to those with no schooling (5.4%), primary (3.2%), college (6.5%) and university education (1.1%). Disaster intervention is the least used innovation in the study area, with only 1 male using it. Smart irrigation is used by 2.2% of females and 3.3% of males with secondary education.

Table 4.2: Relationships between gender, age, education and employment status (in percentage) and the use of innovations, technologies and practices.

Innovations, technologies and practices	Gender	%	Education	%	Employment status	%
Rainwater	Female Male Missing	34.4 24.7	No schooling Primary Secondary TVET/College University Missing	3.2 8.6 3.6 7.5 1.1 2.2	Formal Informal Unemployed Retired Missing	4.3 11.8 36.6 5.4 3.2
Groundwater	Female Male Missing	1.1 6.5 0	No schooling Primary Secondary TVET/College University Missing	0 0 4.3 2.2 1.1 0	Formal Informal Unemployed Retired Missing	3.2 1.1 2.2 1.1 0
Water recycling	Female Male Missing	14.0 17.2 0	No schooling Primary Secondary TVET/College University Missing	1.1 4.3 19.4 5.4 1.1 0	Formal Informal Unemployed Retired Missing	4.3 9.7 15.1 1.1 1.1
Reducing water loss	Female Male Missing	1.1 1.1 1.1	No schooling Primary Secondary TVET/College University Missing	0 0 2.2 0 0 1.1	Formal Informal Unemployed Retired Missing	0 0 2.2 0 1.1
Conservation Agriculture	Female Male Missing	22.6 19.4 1.1	No schooling Primary Secondary TVET/College University Missing	5.4 3.2 25.8 6.5 1.1 1.1	Formal Informal Unemployed Retired Missing	5.4 7.5 23.6 5.4 1

Table 4.2 Continue….

Innovations, technologies and practices	**Gender**	**%**	**Education**	**%**	**Employment**	**Gender**
Smart irrigation	Female Male Missing	2.2 3.2 0	No schooling Primary Secondary TVET/College University Missing	0 0 5.4 0 0 0	Formal Informal Unemployed Retired Missing	0 1.1 3.2 1.1 0
Sustainable intensification	Female Male Missing	7.5 2.2 1.1	No schooling Primary Secondary TVET/College University Missing	1.1 1.1 7.5 1.1 0 1.1	Formal Informal Unemployed Retired Missing	0 3.2 5.4 1.1 2.2
Disaster Intervention	Female Male Missing	0 1.1 0	No schooling Primary Secondary TVET/College University Missing	0 0 1.1 0 0 0	Formal Informal Unemployed Retired Missing	0 1.1 0 0 0
Behaviour changes interventions Agric.	Female Male Missing	2.2 5.4 1.1	No schooling Primary Secondary TVET/College University Missing	0 0 4.3 2.2 1.1 1.1	Formal Informal Unemployed Retired Missing	4.3 1.1 2.2 0 1.1

4.2 Water innovations, technologies and practices in the study area

Water innovation, technologies and practices components were categorised into seven (7) different groups, which are components within the group that had their own sub-components (rainwater, groundwater, water recycling, river streams, reducing water loss, waterage technology and other indigenous water use-related innovations, technologies and practices). In this study, the above-mentioned water-related components are regarded as either innovations, technology or practices looking at innovative ways in which these water sources are being utilised, practiced, extracted and practised for domestic use, irrigation and industry-related uses. This will aid in understanding different innovative ways to preserve available water resources.

Respondents were asked to select which innovation(s) and practice(s) they were currently using in their households, how they are using such innovation, and give the reasons they were using it and the challenges of using the innovation they selected.

Figure 4.1 was plotted from the data collected where multiple responses, which included different water sources used at the household, were obtained (i.e., a household can state multiple water sources). Respondents were inquired about the source of water that they utilize most frequently at the household level and whether they treat the water from the source. Most respondents (47.3%, n= 44) utilise communal municipal tap water. However, responses differed in terms of the water source. At their residences, 30.1% (n= 28) of respondents use municipal tap water, while most of them use this water untreated because they assume that municipal water treatment facilities have already treated it.

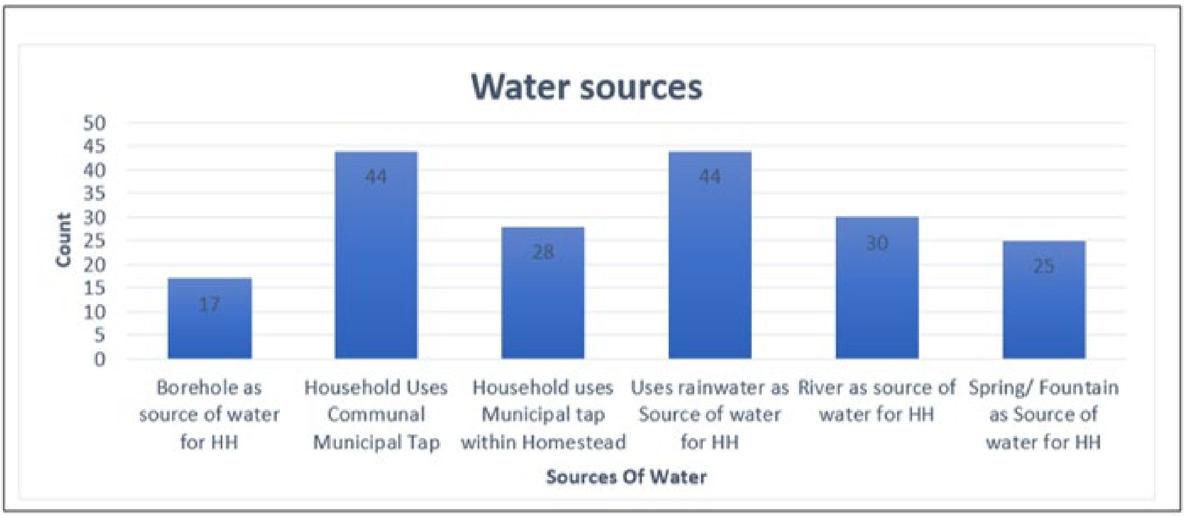

Figure 4.1: Different water sources used at the household level in the study area.

Most respondents (47.2%, n= 44) were utilizing rainwater as water source, which is a high proportion of the sampled population (Figure 4.1). Most of the respondents collected rainwater using different innovative ways, such as channelling rainwater from the roof into JoJo tanks using gutters. Still, some also used buckets and dishes to conserve water and act as a backup if municipal water supplies were unavailable. Only a small portion of the sampled population obtains water from boreholes (18.3%), primarily for domestic use. Due to a lack of municipal water or boreholes in their homes, 32% (n= 30) and 26.9% (n= 25) of the respondents collect water from rivers and springs/fountains, respectively (Figure 4.1).

Most of the rivers and springs/fountains in the research region are located at a distance of 2 km or less. A lower proportion of respondents (18.3%; n= 17) stated that they use boreholes within their own households to have easy and reliable access to water resources. Most people lack the capital and maintenance resources needed for a borehole, which is why fewer people than expected have one in their houses (Figure 4.1).

Similar findings were reported in the study by Koppen *et al*. (2020), which highlighted the use of multiple water sources for various purposes in rural communities within Limpopo, including Khalavha and Tshakhuma. The study revealed that rainwater harvesting is a prevalent practice, with methods ranging from well-designed roofs equipped with gutters and storage systems to the more basic approach of placing buckets outdoors to collect rainwater. A minority of households not engaged in rainwater harvesting were found to lack the necessary infrastructure, such as proper corrugated roofing. Additionally, the study indicated that over half of the households in the sample engage in water reuse, with the highest proportion reaching 80%. This practice was consistent across the six villages studied. Water from activities such as washing, bathing, or laundry is repurposed for irrigation of trees, flowers, lawns, and, in some cases, vegetables. Those who do not reuse water cited access to municipal tap water as the primary reason, as the municipal borehole system provides water free of charge on alternate days to most of the villages. Furthermore, the study by Koppen et al. (2020) found that in four of the six villages, 71% to 91% of households utilize two or more sources of water, aside from rainwater harvesting.

Figure 4.2 displays six (6) distinct sources of water along with the respondents' treatment of the various sources of water or lack thereof. According to the survey, just 9.7% (n= 9) of the 18.3 (n= 17) of the respondents who use borehole water in their households treat the water before consumption, while only 21.5% (n= 20) of those who use communal municipal tap water (47%, n= 44) use a central water treatment method.

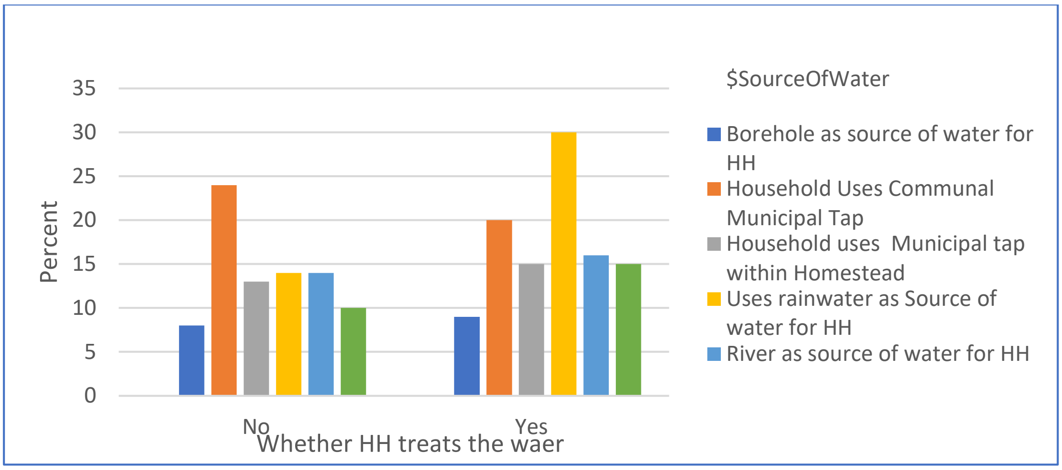

Figure 4.2: Source of water vs water treatment.

It was noted that the greatest percentage of people who treat water are those who use rainwater. This was because rainwater easily gets contaminated within a short period after collection. Some noted that rainwater quality degrades within 5-7 days of collection. Thus, they treat it with different water treatment methods, including boiling, adding bleach and coarse salt, among others. Due to open rivers' heightened pollutant exposure, only 16.1% (n= 15) of 26.9% (n= 25) and 17.2% (n= 16) of 32.3% (n= 30) of respondents who use spring/fountain and river water, respectively, treat water. Overall, most respondents who do not treat water lack knowledge and claim that neither the government nor the community leaders have done anything to address the water problem, let alone water quality.

The relationship count in Figure 4.3 illustrates the linkage or connection that exists between various components. The connection is visually represented by nodes and linkages as weak, normal, and strong linkage. The red, green, and blue nodes indicate the distance from the source, the type of water treatment, and the source of water used at the household level. The water source-treatment-distance relations map shows a substantial association between respondents who use municipal tap water for their homes and community tap water that has not been treated. Only a minor percentage of respondents use coarse salt and the boiling method of water treatment. This is because most people who use these water sources rely on municipal water treatment (central chlorination). Thus, they do not see the need to treat the water.

Most respondents who use communal municipal water for household consumption collect water within one km of their homes, as evidenced by the strong relationship between respondents who use communal municipal water and the distance within one km of the household (Figure 4.3). During the assessment, it was discovered that residents either use a wheelbarrow or connect a small pipe to the communal tap to collect water. People who obtain water within households either use municipal water systems or household boreholes without treatment.

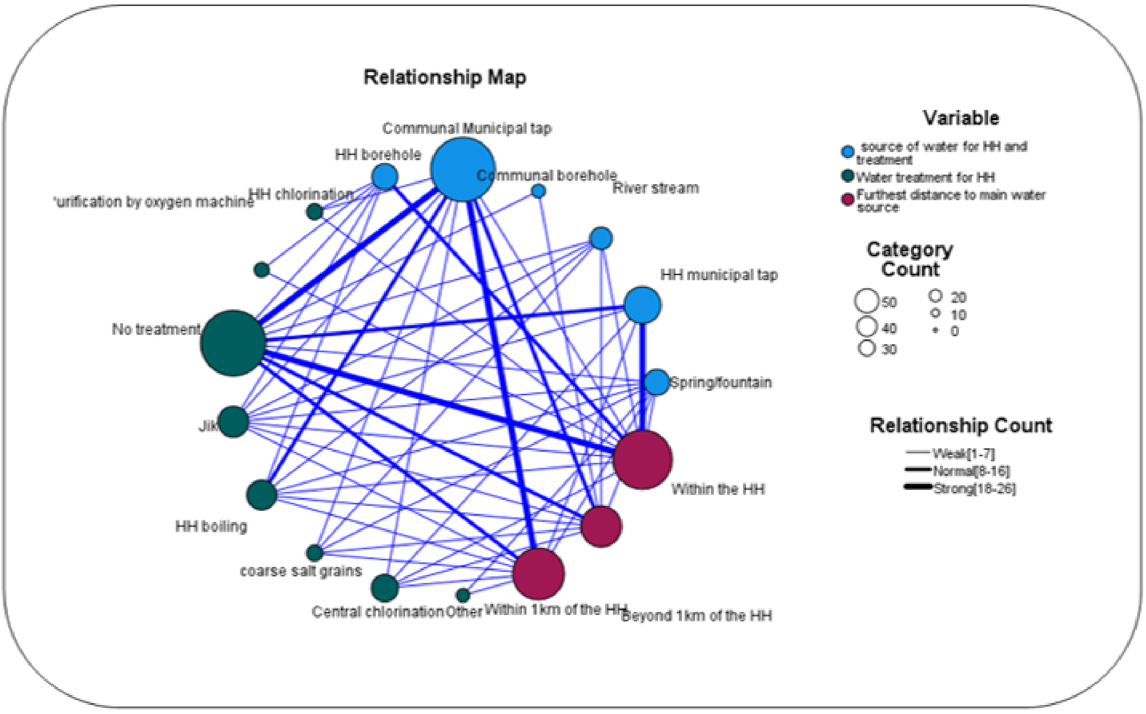

Figure 4.3: The relationship between water treatment methods, source of water and distance to the source.

In this section of the study, multi-response answers are allowed, and the respondents could select one or more possible options that apply to them. The total number of overall respondents was 93 for all six villages. In this study, water smart technologies, innovation and practices refer to a range of methods used to access water and bring solutions aimed at Enhancing the sustainable management, utilization, and conservation of water resources. These initiatives are designed to enhance water efficiency, reduce waste, and address water scarcity, pollution, and overall water quality challenges. Examples include the reducing loss method, use of technologies (smart metering, generator, roof harvesting, the use of generator to draw water, as well as recycling). Different smart innovations, technologies and practices, their uses, types and challenges are shown in Table 4.3.

Table 4.3: Different water innovations, technologies and practices used in the study area

	practices							
Variables	**Rainwater practices**	***f***	**Groundwater practices**	***F***	**Water recycling practices**	***f***	**Water loss reduction practices**	***f***
	Total number of respondents using rainwater	57	Total number of respondents using groundwater	7	Total number of respondents using water recycling	29	Total number of respondents using water-reducing loss	**3**
Type of innovation, technology or practise used	Roof harvesting	57	Generator	5	Grey water	29	Cover	2
			Hand drawn	1			Monitoring and reporting	1
			Motorised	1				
Uses of innovation, technology or practise	Domestic	47	Domestic purposes	7	Irrigation	25	-	
	Irrigation	28			Sanitation	4		
	Sanitation	28						
Reasons for using innovation, technology or practise	Cheap	2	Frequent drought	5	Water saving	27	Water scarcity (Saving available water)	3
	Easy to use	7						
	Frequent drought	21	Unreliability of municipal supply	1	Unreliability of municipal supply	4		
	Unreliability of municipal supply	13						
	Water saving	11	Only Source available	1				
	Far from Source	3						
Challenges	High initial cost	2	High initial costs	2	Unsustainable for irrigation	13	Lack of knowledge	1
	Unsustainable roof	2						
	Low quality	28	High maintenance costs	4	Not enough water	5	None	2
	Limited storage	11	Health problems	1	None	9		
	None	14						
innovation, technology or practise ranking	Extremely poor	5	Extremely poor		Extremely poor	_	Extremely poor	
	Very poor	6	Very poor	_	Very poor	4	Very poor	-
	Poor	15	Poor	_	Poor	4	Poor	
					Neutral	7	Neutral	2
	Good	14	Good	4	Good	7	Good	1
	Excellent	13	Excellent	3	Excellent	7	Excellent	-
	Missing	4	Missing	-	Missing	-	Missing	-

f = denotes the total number of respondents

Only four of the seven components listed as part of water innovation, technologies, and practices were discovered to be in use in the study area, though this varied from village to village (Table 4.3). The most used water innovations were roof harvesting, groundwater harvesting technology (generator and hand-dug), water recycling, and water loss reduction.

According to the survey, 57 of the 93 respondents from all six villages used rainwater (roof harvesting) as a water source, with each respondent using this innovation for a different reason and encountering a different set of challenges (Table 4.3). According to the study, 82.5% (n= 47) of the respondents used roof harvesting techniques for domestic purposes such as drinking and cooking. There were 49.1% (n= 28) respondents who reported utilising this innovation for irrigation, and 49.1% (n= 28) who indicated that they were using it for sanitation. This is because these villages' municipal taps are constantly dry, forcing residents to rely on rainwater for irrigation and domestic use.

Respondents were asked why they were using rainwater and indicated that they were using it due to water saving (19.3%; n= 11) and unreliable municipal supply 22.8% (n= 13). Many people are substituting treated water with rainwater because of water shortages. For these reasons, many individuals turn to using rainwater as a source of household water consumption. In addition, some respondents indicated that tap water is only available once every two weeks. At the same time, in some locations, they do not obtain municipal tap water for three months.

Roof harvesting technology was used by those who constantly buy water in bulk since it is more affordable and readily available. Only 14 respondents indicated that they have no concerns or challenges with roof harvesting, even though many respondents 49.1% (n= 28), said their biggest challenge with rainwater harvesting is that it develops contaminants more quickly, and (19.3%; n= 11), who said their biggest challenge is having limited storage space (Table 4.3). Respondents who rated the importance of rainwater harvesting in the household as poor (26.3%; n= 15), good (24.6%; n= 14) and excellent (22.8%; n= 13) were higher than those who rated it as very poor (10.5%; n= 6). Only four respondents were missing out of those who assessed the household's importance of rainwater (Table 4.3).

Kahinda and Taigbenu (2011) examined the challenges and opportunities associated with rainwater harvesting in South Africa. Their findings indicated that rainwater harvesting has significant potential to enhance water productivity in dryland agriculture and support homestead gardening. However, the study also emphasized the challenges and opportunities within the South African context. Kahinda and Taigbenu

(2011) further noted the diversity of techniques available for rainwater harvesting, while recognizing the limited efforts to quantify the ecohydrological impact of widespread adoption at the quaternary catchment scale.
Badisa (2011) investigated the adoption of in-field rainwater harvesting technology for improving cropland productivity in Lambani village, Thumela local municipality. The results of Badisa (2011) align closely with the findings of the present study, as depicted in Figure 4.4, which illustrates factors influencing the adoption of water innovations, technologies, and practices. Furthermore, Badisa (2011) advocated for increased political and institutional involvement in the implementation of in-field rainwater harvesting technologies.
Matimolane *et al*. (2023) explored the determinants of rainwater harvesting practices within rural communities in Limpopo Province, South Africa. The study revealed that 63.8% of the households surveyed practiced rainwater harvesting to supplement available water for domestic use, although relatively few households used the harvested water for potable purposes. In comparison, the present study found that 57 out of 93 (61.3%) households employed rainwater harvesting (see Table 4.3).

In this study, seven respondents used groundwater as a wastewater source, but only 71.4% of them reported using generator (both electrical and diesel generators) technology for groundwater abstraction (Table 4.3). Only 2 respondents were found to be using hand-drawn and motorised pump technology. All the respondents used groundwater for domestic purposes because these boreholes are located within their households. About 14.3% (n= 1) of the seven respondents who use groundwater do so because it is their only water source. The other 71.4% (n= 5) use it due to frequent drought in their villages. One respondent indicated they use groundwater because the municipal water supply is unreliable (Table 4.3).

The most challenging part of using groundwater is the high maintenance cost associated with drilling and maintaining a borehole. This is because boreholes encounter problems such as fracturing, collapsing, losing circulation, damaged pumps, installing filtration systems to ensure the best possible water quality, or drying up boreholes, among others. One respondent expressed concern about health issues due to the high salinity of groundwater. Two others expressed concern about the high initial costs, as borehole water installation can be very expensive. The importance of groundwater was rated as good and excellent, because groundwater is reliable and readily available (Table 4.3).

Odiyo and Makungo (2018) assessed groundwater quality from private boreholes in Siloam village, located in the Limpopo Province of South Africa, focusing on its suitability for domestic use and identifying potential contamination sources. The study highlighted that rural communities frequently construct boreholes within their residential premises, making them susceptible to contamination and related health risks. This underscores the need to educate borehole owners on strategies to reduce groundwater contamination, thereby addressing the challenges of low water quality identified in the current study. MacDonald and Davies (2000) reviewed the use of groundwater for rural water supply in sub-Saharan Africa, identifying several challenges such as overexploitation, contamination, costs and high maintenance of boreholes, and the need for appropriate technological, economic, and social choices in water technology. Their findings highlighted issues that align with some of those encountered by respondents in the current study.

A total of 29 respondents recycled water in the form of grey water, with 86.2% (n= 25) of the 29 respondents using grey water for irrigation and only 13.8% (n =4) of the respondents were using it for sanitation purposes such as mapping and flushing toilets (Table 4.3). A minor percentage of 13.8% (n= 4) respondents were using grey water due to unreliable municipal supply, while those who reported that they were using water recycling technology for a reason to save water were found to be 100% (n= 29), as they would rather save the limited water that they have for household essentials and use grey water for irrigating since they are already struggling to have access potable water.

The study discovered that 44.8% (n= 13) of respondents faced the challenge of unsustainable greywater use, since greywater has the potential to harbour pathogens (Table 4.3). Bacteria and viruses in water can kill or harm some plants and trees. About 13.8% (n= 4) of respondents cited a shortage of water as a challenge, while 31.0% (n= 9) revealed that they faced no challenges with grey water they use in their households. Grey water was rated very poor by four respondents, excellent by seven, poor by seven, and neutral by seven.

Radingoana *et al*. (2019) investigated perceptions of greywater reuse for household gardening in two rural villages within the Fetakgomo Local Municipality, South Africa. Their findings indicate that 66% of respondents in Ga-Nkwana utilized greywater for gardening, compared to 59% in Ga-Seroka. Furthermore, 39% of participants in Ga-Nkwana and 40% in Ga-Seroka employed greywater for irrigating fruit trees, while 24% and 22% of respondents in Ga-Nkwana and Ga-Seroka, respectively, used greywater for irrigating non-raw vegetables. These findings align with the current study, where 86.2% of respondents used greywater for irrigation, and only 13.8% used it for sanitation purposes like mopping and flushing toilets (Table 4.3).

Murei *et al*. (2011) conducted a study examining the barriers to the implementation of Water and Sanitation Safety Plans (WSSPs) in rural areas of South Africa, with a specific focus on the Vhembe District in Limpopo Province. The findings indicated that factors such as poverty, unemployment, limited access to purified water and inadequate sanitation infrastructure have contributed to the prevalence of waterborne diseases within these communities, thereby significantly impeding the successful implementation of WSSPs. Consequently, the study highlighted the necessity of educating community members on appropriate sanitation-related behaviours and perceptions. Furthermore, it emphasized the importance of collaborative efforts involving various stakeholders, including men and women from diverse cultural and religious backgrounds, to address these barriers effectively. Such an approach is essential for mitigating health risks associated with water supply, wastewater reuse, and sanitation in rural communities.

Water loss reduction is an innovative solution to water scarcity and the findings of this study highlighted that only a few numbers of individuals in the study area understood how it works. Therefore, only a few respondents practised it in their homes. Three respondents agreed to practice water loss reduction in their homes, with two of the three respondents covering their wells, tanks and bins located outside to prevent water loss through evaporation and other factors (Table 4.3). Others responded that they monitor and report leaking pipelines and distribution systems to the authorities in the municipality. To these respondents, this was a way of saving already available water. One participant stated that the lack of knowledge on water loss reduction is extremely challenging because they are unaware of any other effective smart technologies that may be utilised to prevent water loss. Two of the three respondents rated water loss reduction as neutral, while one thought it was a good, innovative technology.

Dighade *et al.* (2014) examined the challenges of managing water loss in water distribution systems in developing countries. The study identified that many water loss issues in rural areas stem from ageing infrastructure, community behaviour, supply hours, and system pressure. It emphasized that a diagnostic approach, supported by practical and achievable solutions, can be applied to any water distribution system in a developing country to create an effective water loss management strategy. The findings from Dighade et al. (2014) are consistent with the current study, as only a few people in the study area understood the system. Those who understood water loss reduction proactively monitored and reported leaking pipelines and distribution systems to municipal authorities (Table 4.3).

One of the primary challenges to decreasing water loss in rural regions is ageing infrastructure (Smith, 2018). Many rural water supply systems have ageing pipes, pumps, and storage facilities, resulting in high leakage rates (Jones *et al*., 2019). Limited financial resources compound the problem, impeding investment efforts in infrastructure improvements and maintenance (Brown & White, 2020).

4.2.1 Factors influencing the adoption of water innovation technologies

Figure 4.4 depicts the various influences on the adoption of water innovations and practices, where multiple responses were permitted since respondents were influenced by various factors. Most of the respondents (49.5%; n= 46), (44.1%; n= 41), (43.0%; n= 40), (43.0%; n= 40) reported that knowledge, cost savings, finance, and reliability influenced their use of water innovations, technologies and practices, respectively. Due to a lack of municipal water supply, most respondents relied on water practices such as roof harvesting and groundwater abstraction technologies. At the same time, those with sufficient funds drilled their own boreholes at home for high reliability.

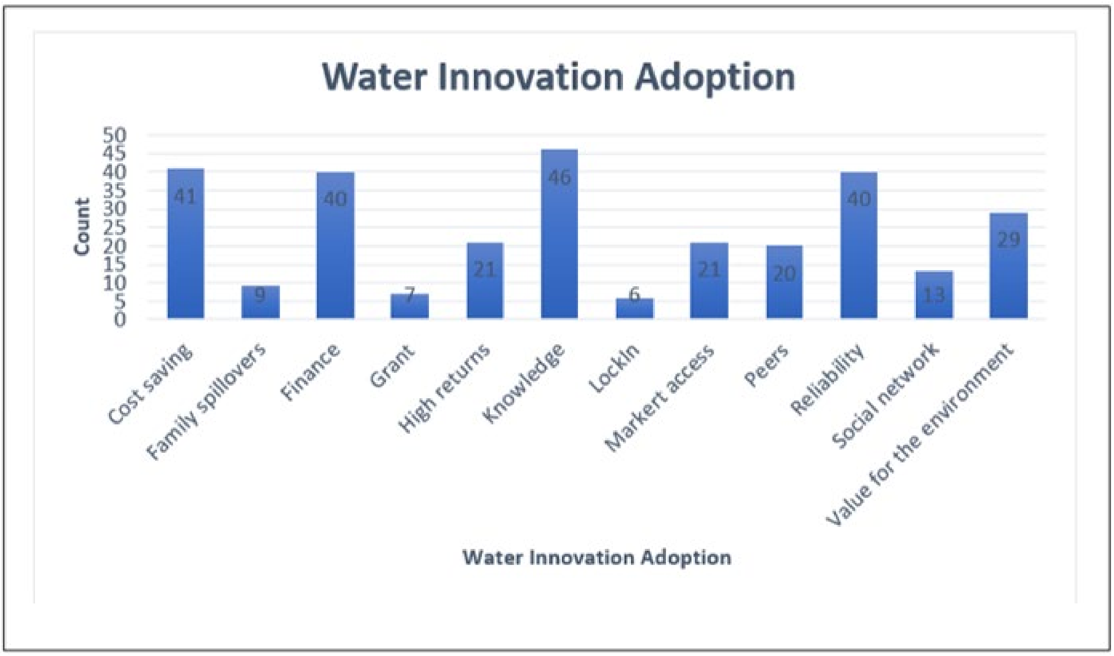

Figure 4.4: Factors affecting the influence of the adoption of water innovations.

During the survey, minor respondents 7.5% (n= 7) stated that they use grant money to either buy bulk water or pay people to fetch water for them as they cannot afford household taps or boreholes in their homes. Regarding the environment, most respondents (31.2%) admitted using rainwater, water loss reduction, water recycling and groundwater-related innovations to preserve the environment. For instance, using rainwater innovation helps reduce stormwater runoff while increasing the durability of roads. By eliminating runoff, contaminants such as pesticides, sediments, metals, and fertilizers that could lead to polluting surface water could also be reduced, as the peak flow volume and velocity of the storm in nearby creeks, streams, and rivers can be lessened; erosion could be reduced, thus encouraging sustainable and environmentally sound ways of living.

4.3 Energy sources innovations, technologies and practices

Non-renewable energy (NRE) and renewable energy (RE) were used to categorise energy innovation, technologies and practices. The NRE was thus categorised into coal, electricity, and paraffin, while RE was divided into biogas, solar (photovoltaic

(PV) or solar water heater), and wind. Multiple responses were permitted and considered in this study area.

Figure 4.5 shows that electricity and firewood are the most frequently used energy sources, with 94.6% (n= 88) and 95.7% (n= 89) of respondents using this sort of energy source, respectively. Though most people face obstacles when it comes to using electricity and biomass related technologies and practices, most of them are using these smart practices because of their reliability and availability. A minor percentage of 10.8% (n=10), 4.3% (n= 4), 2.2% (n= 2) and 4.3% (n= 4) use solar, paraffin, coal, and biogas as energy sources, respectively.

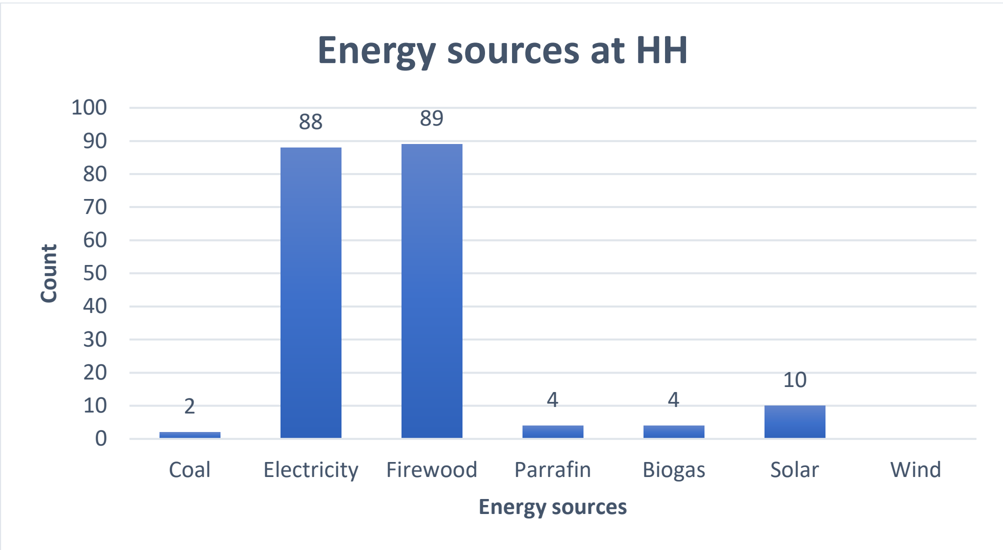

Figure 4.5: Sources of energy used at the household level within the study area

The results also showed that individuals who use solar energy in their homes mainly utilise it in the form of solar water tanks or water heaters, as well as for lighting, whereas those who use paraffin use it in the form of paraffin stoves for cooking and heating during load-shedding. One individual acknowledged utilising dung as a source of energy. The respondent further explained that they use dried cow dung to make a fire during winter or for cooking. The survey also found that while most people depend on electricity, they also use these other forms of energy as fallbacks in the event of power outages, malfunctions, or financial constraints. The communities must be educated because none of the respondents were using wind energy, and they lack information and understanding of how wind energy innovation may be used in practice and to their own advantage.

Bohlman and Inglesi-Lotz (2018) evaluated South Africa's residential sector energy features from the perspective of energy-use profile, geographical distribution, and demographic aspects of the sector. Even so, South African households, the majority of whom are of low-income, do not merely use the national grid and electricity to fill their basic energy needs; with 50 kWh of free electricity afforded each month to poor households connected to the national grid. Rather, they continue to use multiple energy carriers to satisfy their basic energy needs, including wood and paraffin (see: Solarin *et al*., 2020). A large part of the population, especially in rural areas, relies on solid fuels (e.g., wood, coal, dung) for their energy requirements, with an estimated 75% of the non-electrified household's dependent on solid fuels for cooking, heating, and lighting. Lighting – 5–10 percent of total energy consumption – is the dominant household electricity use in South African low-income households, while the remaining 85–90 percent is made up of heating and cooking.Similar to the present study are the findings from Bohlman and Inglesi-Lotz (2018).

Masekoameng *et al*. (2005), assessed residential energy requirements and usage patterns in the rural communities of Giyani, located in Limpopo Province, South Africa. The results of this study showed that firewood is the main source of energy for cooking and heating while paraffin and candles are mainly used for lighting. Few households supplement firewood with paraffin when the wood is not available or in case of rainy conditions. Comparing the results by Masekoameng., (2005) to the current study, both studies show that firewood is widely used as the primary energy source within the study area.

Figure 4.6 displays seven (7) usages of energy used at the household level within the study area. Different sources of energy have their own different uses, and the amount of energy devoted to specific uses which the respondents are using distinctively as shown in the graph above. The energy needs for these different households vary, but when viewed as a whole, more than half of the energy used in households is used just for a few functions, namely cooking, lighting, appliances, and heating, where the major proportion was found to be 95.7% (n= 89); 84,9% (n= 79); 82.8% (n= 77); 81.7% (n= 76) and 77.4% (n= 72), respectively.

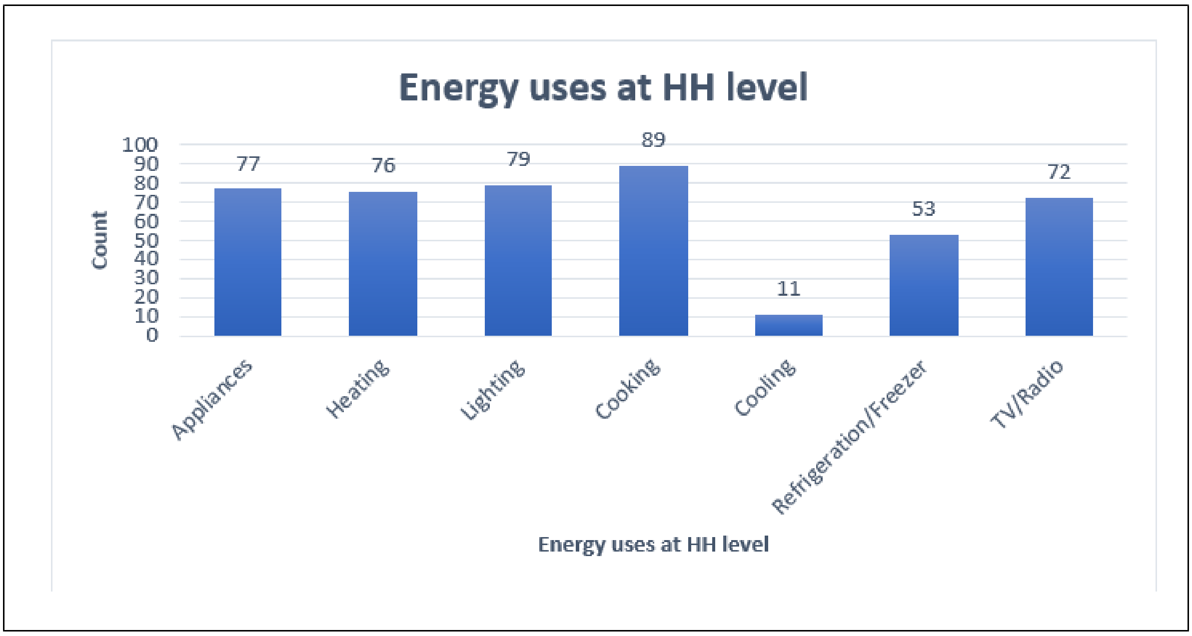

Figure 4.6: Different energy sources used at the household level in the study area.

Figure 4.6 also shows that 11.8% (n= 11) of those with ventilators, air conditioning and fans responded that they use electricity to cool their households to keep homes at a comfortable temperature. Air conditioning accounts for a much smaller share of household energy use. 57% (n= 53) of the respondents indicated that they have refrigerators/freezers in their homes, which they use as preservation methods (Figure 4.6).

The relationship map (Figure 4.7) demonstrates the relationship that exists between the type of energy used at the household (indicated with blue nodes) and the primary use of energy at household level (indicated with green nodes). It was determined that most of the respondents use many different energy types but only rely on three (electricity, biomass and paraffin) sources as their main type of energy source, which are electricity, biomass, and paraffin is mostly used by those who have no electricity since they have no alternative energy source. The map shows that above 60 counts of the respondents mainly use electricity for lighting and a minor count of respondents use electricity for heating, television and refrigeration. Those using biomass mainly use it for cooking, while a minor count of those using paraffin use it for heating water for bathing or cooking.

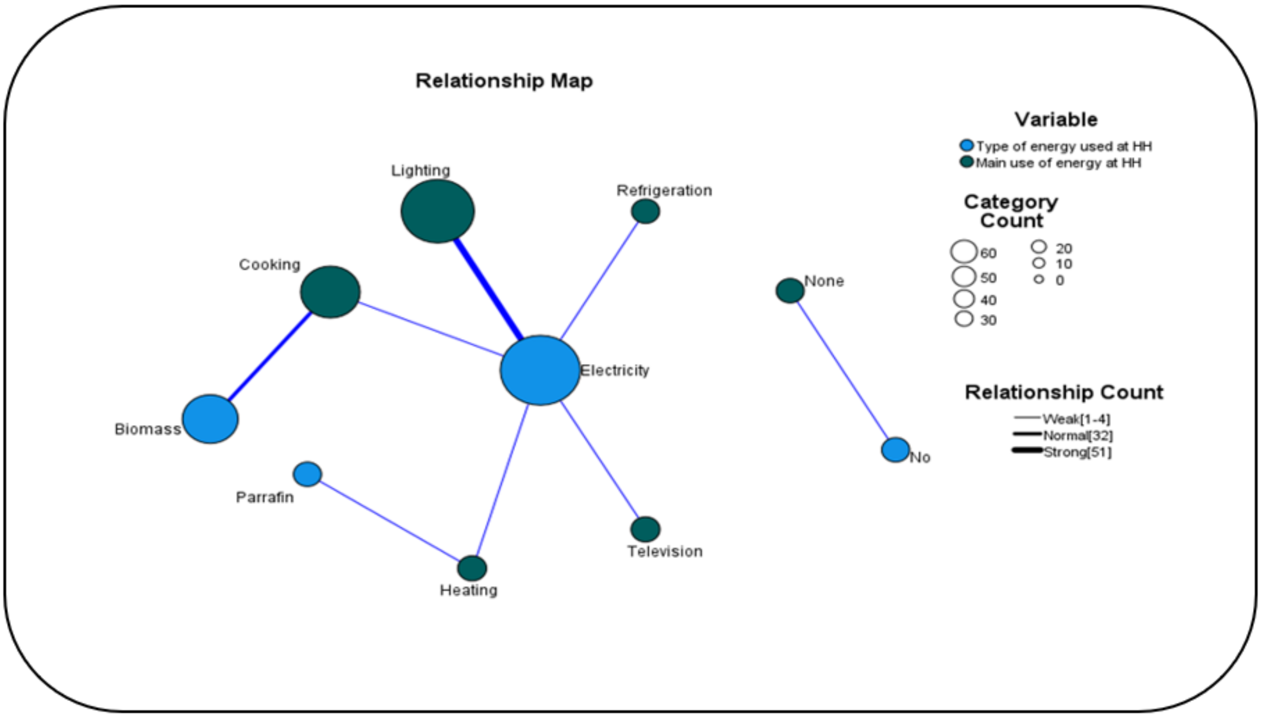

Figure 4.7: Relationship between the type of energy and main use of energy

The NRE are resources that cannot be replaced or renewed once they are used up. All four (4) types of NRE sources investigated through the questionnaire survey were found to be used in the study area but vary in the way they are utilised (Table 4.4). Energy smart technologies, innovation and practices refer to the application of advanced technologies, innovative approaches, and efficient practices in the energy sector. This concept encompasses a range of strategies and solutions aimed at optimising the generation, distribution, and consumption of energy to achieve improved sustainability, efficiency, and environmental performance. Examples include smart grids, LED Lighting, use of solar and other renewable energy.

Table 4.4: Non-renewable energy related smart innovations, technologies and practices used in the study area.

	Non-renewable Energy Innovations							
Total number of respondents using NRE	93							
	Coal	*f*	Electricity	*f*	Firewood	*f*	Paraffin	F
	Total number of respondents using Coal	2	Total number of respondents using electricity	88	Total number of respondents using firewood	89	Total number of respondents using paraffin	4
Uses of innovation technology	Heating	2	Lightning	77	Heating	1	Lightning	2
			Cooking	8	Cooking	88	Cooking	1
			Refrigeration	3			Heating	1
Reasons for using innovation technology	Cheap	2	High cost of alternative	9	High cost of alternative	12	Easily available	1
			Easily available	45	Easily available	23	Cheap	1
			Cheap	1	Cheap	35	Loadshedding	2
			Convenient	27	Loadshedding	7		
			Lock-ins (modern, only source, culture)	4	Convenient	5		
					Reliable	4		
			Missing	2	Missing	4		
Challenge(s)	Pollution	2	High cost	31	Pollution	3	Pollution	3
			Lack of awareness	2	Bulkiness	5		
					Cost	3		
					Lack of awareness	1	None	1
			Loadshedding	8	Distance to source	28		
			It is Dangerous	35	Not user-friendly on rainy days	31		
			None	7				
			Missing	5	None	17		
					Missing	1		
Innovation technology ranking	Extremely poor	0	Extremely poor	15	Extremely poor	0	Extremely poor	0
	Very poor	0	Very poor	9	Very poor	5	Very poor	0
	Poor	0	Poor	0	Poor	5	Poor	0
	Neutral	0	Neutral	0	Neutral	13	Neutral	0
	Good	2	Good	30	Good	30	Good	3
	Excellent	0	Excellent	13	Excellent	30	Excellent	1
	Missing	0	Missing	3	Missing	6		

Coal was found to be used by only two respondents, who used it as coal heaters for heating their homes during cold weather conditions and keeping their families comfortable. Both respondents stated that they are using coal because they find it affordable, as it is mostly used as a domestic energy source by low-income households because it is cheap. The respondents also noted pollution as a challenge that they face when using coal as a source of energy. This was because the sulphur dioxide released from the coal polluted the air. However, all coal is not of the same quality; have high moisture content that can pollute the air, which can cause various diseases such as asthma. The respondents rated coal as being a good source of energy.

The study indicated that 87.5% (n= 77) of 88 respondents who were using electricity-related smart innovation, technologies and practices responded that they mainly use it for lightning due to the high cost of electricity, while others are using it for cooking 9.1% (n= 8) and for refrigeration and 3.4% (n= 3) (Table 4.4). Most of the respondents use electricity because it is easily available, 51.1% (n= 45) compared to the other energy sources as they can buy electricity in various places, while 30.7% (n= 27) respondents stated that they use electricity because it is convenient for them. This is because, for most people, electricity is an essential part of modern life, making life easier without putting in much effort. The remaining 1.2% (n= 1), 4.5% (n= 4), and 10.2% (n= 9) gave reasons that they are using electricity because it is cheap, due to lock-ins and the high cost of alternatives, respectively.

In addition, 39.8% (n= 35) respondents reported that their main concern with using electricity is that it is very dangerous to use as it can cause shock, electrocution and burns if not handled with care or in case of faults or explosions. Another major percentage (33.3%; n= 31) was of those who stated that the high cost of electricity is a challenge (Table 4.4). The results also showed that eight people reported load-shedding as their major challenge. This is because there is a deliberate shutdown of electric power as an action to reduce the load on the use of electricity supply to avoid excessive load on the generating plants. This disadvantages those who are relying mainly on electricity for household essentials. The remaining 7.9% (n= 7) respondents did not have challenges about electricity, and 5.7% (n= 5) did not specify their challenges. Electricity was rated good by 34.1% (n= 30), excellent by 14.8% (n= 13), and the remaining 15.9% (n= 14) and 10.2% (n= 9) rated electricity extremely poor and very poor, respectively while the other 3.4% (n= 3) did not specify their ratings.

A total of 95.7% (n= 89) of the respondents revealed that they were using firewood-related smart innovation, technologies and practices. Some of the households created smart fireplaces for cooking, and braaing while some use fireplaces for heating their households. Out of 95.7% (n= 89) respondents 98.9% (n= 88) were using it for cooking, and only 1.1% were using it for heating. The majority of those using firewood were of the reasons that it is cheaper and easily available; this is because most people collected firewood from the woods by themselves and those buying it get it at a cheaper price compared to other energy sources. It was determined that 13.5% (n= 12) were using it because of the expensive cost of alternatives is expensive while others were using it because it is reliable and convenient.

The most challenging things for those who collect firewood are the distance to the source (31.8%; n= 28) and bulkiness (5.7%, n= 5), as some have to go to mountains to get firewood and carry it to their households (Table 4.4). A minor percentage stated pollution (3.4%, n= 3), high cost (3.4%, n= 3), and lack of awareness (1.1%, n= 1) as challenges that they face regarding using firewood.

Only four respondents used paraffin related smart innovation, technologies and practices, which are used for lighting, cooking and heating. Respondents further explained that they use paraffin lamps to light up their homes, while others use paraffin stoves. The results showed that 50% (n= 2) of the four respondents were using paraffin as an alternative due to load-shedding, while others gave reasons for it being cheap (25%; n= 1) and easily available (25%, n= 1). The challenge of using paraffin is pollution as they have a high level of emissions, which is mostly given off in small, enclosed spaces, as well as harmful vapour, which can cause health issues. Paraffin was rated good (75%; n= 3) and excellent (25%; n= 1).

The total number of respondents using solar energy-related smart innovation, technologies and practices was 10 (10.8%) out of 93 (n= 100%) within the study area (Table 4.5). A percentage of 50% (n= 5) were using solar-related smart innovations, technologies and practices for heating through solar water heaters, while 40% (n= 4) were using them for lighting in their households. The remaining 10% (n= 1) was using solar energy for charging accessories. Solar energy is not only good for the environment by being a clean, green source of energy, but it also decreases costs as some of the respondents in the study area are using it because they are avoiding the high costs of alternatives. It was noted that 40% (n= 4) of the respondents use solar energy because it is easily available, while 30% (n= 3) use it because it is cheaper.

Table 4.5: Different Renewable energy innovations and practices that are used in the study area (n= 93)

	Solar	*f*	Biogas	F
	Total number of respondents using solar	10	Total number of respondents using biogas	4
Uses of innovation technology	Lighting	4	Heating	1
	Charging accessories	1	Cooking	3
	Heating	5		
Reasons for using innovation technology	High-cost alternative	1	Convenient	1
	Easily available	4		
	Cheap	3	High cost of alternative	3
	Convenient	2		
Challenge(s)	High initial cost	1	Pollution	1
	Weather constraints	7		
	None	2	Missing	3
Innovation technology ranking	Extremely poor	0	Extremely poor	0
	Very poor	2	Very poor	
	Poor	0	Poor	0
	Good	5	Good	1
	Excellent	3	Excellent	3

The obtained results indicated that 70% (n= 7) of the respondents revealed that the challenge they face with using solar energy-related smart innovation, technologies and practices is weather constraints, as weather-dependent solar panels/systems need direct sunlight to gather solar energy effectively. Thus, periods of cloudy and rainy days can have a noticeable effect on the system. The remaining 20% is of those with zero concerns about challenges and those stating high initial cost as a challenge. A major percentage of those using solar energy rated it as good (50%, n= 5) and excellent (30%, n= 3), while a minor percentage rated it to be very poor (20%, n= 2).

The total number of respondents using biogas-related smart innovation, technologies and practices (Efficient Cookstoves) was found to be only 4 (Table 4.5). In rural areas, biogas-related smart innovation, technologies and practices are commonly used for cooking and heating (Rasimphi *et al.*, 2022; Rawat et al., 2016). The study determined that 73% (n= 3) of the respondents are using biogas for cooking, and 25% (n= 1) are using it for heating. A total of 75% (n= 3) indicated that they are using biogas because of the high cost of alternative sources of energy, whereas the remaining respondents are using it for convenience. Although biogas is easy to install, environmentally friendly and requires minimal effort to use, it also has its disadvantages and challenges. The respondents were asked about the challenges they faced with using biogas within their households, and only one respondent stated pollution as a challenge, while the remaining four did not specify the challenges they faced. Biogas was rated excellent (75%; n= 3) and good (25%; n= 1).

Figure 4.8 depicts the various factors influencing the adoption of energy innovations, technologies and practices, where multiple responses were permitted since respondents were influenced by a variety of factors. Most respondents, 52.7% (n= 49), 51.6% (n= 48), 48.4% (n= 45), and 43.0% (n= 40), reported that knowledge, finance, cost saving, and reliability influenced their use of energy innovations, technologies and practices, respectively. Energy innovations, technologies and practices have proven to improve environment quality. The benefits of adopting these kinds of innovations include reduced electricity bills, charges for purchasing generators, and reduced health issues due to air pollution and climate benefits from reduced greenhouse gas emissions. Due to the low energy supply from ESKOM, most people now find other energy sources reliable than electricity; most respondents relied more on firewood, coal and biogas-related smart innovations, technologies and practices, while those with sufficient funds are installing their own solar panels at home for high reliability. Those with enough knowledge understand which alternatives they can use when there is a failure.

Ranganai *et al*. (2022) conducted a study on rural households' perceptions regarding the adoption of rooftop solar photovoltaics (PVs) in the Vhembe District, South Africa. The findings indicated that solar energy was utilized for various household purposes, including water heating, refrigeration, cooking, illumination, space heating, entertainment, and ironing. The participating households generally perceived solar PVs as a cost-effective, user-friendly, and environmentally sustainable alternative energy source that did not require regular payments once installed. The results of Ranganai et al.'s (2022) study align with those of the present study, as illustrated in Table 4.5. In the current study, most respondents indicated using solar energy for lighting, charging accessories, and heating. This preference is primarily due to solar energy being a cost-effective, easily accessible, and convenient alternative to other energy sources.

Rasimphi and Tinarwo (2020) investigated the relevance of biogas technology in the Vhembe District of Limpopo Province, South Africa. Their study revealed that out of 200 respondents, 72 were using biogas, while 128 did not use it due to concerns about the low efficiency of biogas lamps and associated safety issues. As a result, the use of biogas for lighting was generally discouraged.

When compared to the current study, which found that only 4 out of 92 respondents were using biogas, it is evident that biogas is not widely adopted as an energy source in many rural areas. This indicates a lower level of utilization and acceptance of biogas compared to other forms of energy in these communities.

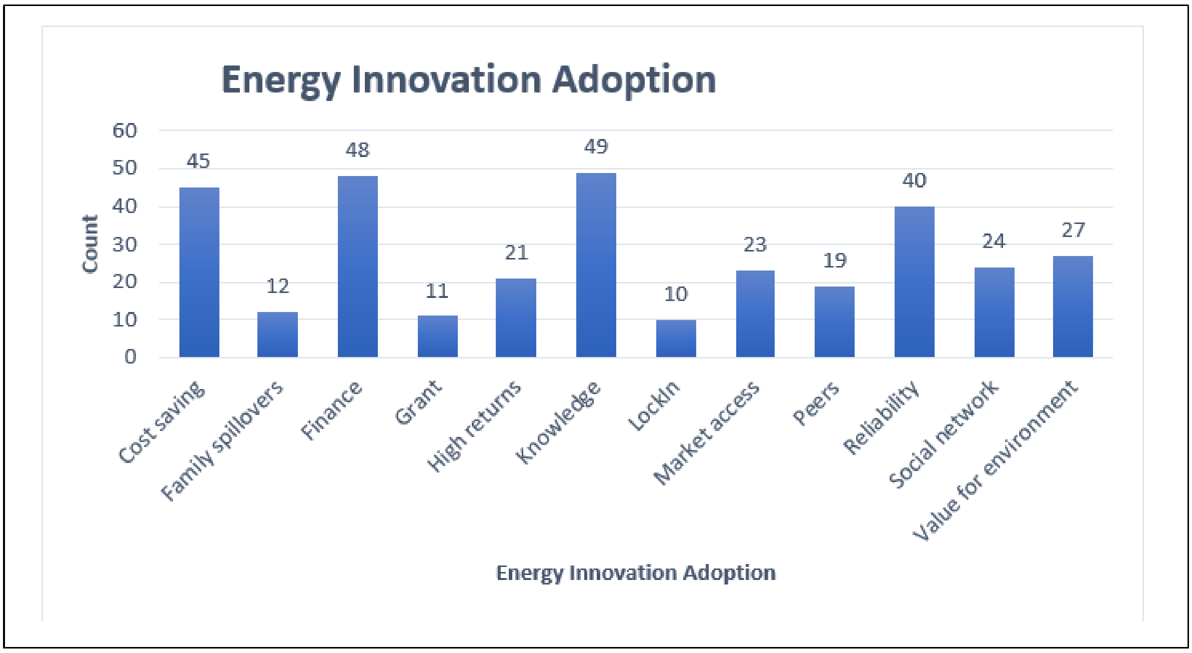

Figure 4.8: Factors affecting the influence of respondent's adoption of energy innovation technologies

During the survey, 11.8% (n= 11) of the respondents stated that they use grant money to have access to energy innovations, technologies and practices within their households to enhance their ways of living (Figure 4.8). Most respondents (29.0%; n= 27) admitted to using these innovations to preserve the environment. For instance, using innovations such as biogas and solar preserve the environment by reducing air pollution. The remaining percentage is of those using these innovations due to social networking (24.8%, n= 24), lock-ins (10.8%, n= 10), high returns (22.6%, n=21) and those that are only using it due to family spillovers (12.9%, n= 12).

4.4 Food innovations, technologies and practices

Figure 4.9 shows the different types of assets that are used to ensure food security within the households of the respondents. Different types of farming practices were stated, and 72.0% (n= 67) of the respondents had home gardens in their backyards wherein they planted different products. Most respondents reported that they have home gardens only to feed their families and have easy and instant access to fresh produce so that they are not forced to visit the grocery stores or farmers market to get vegetables and save money. (47.3%; n= 44); (34.4%; n= 32); (14%; n= 13) had fields within the household, fields outside the household and orchard, respectively. The majority of those who have fields outside/within households, as well as those with orchards, reported that they plant their fruits and vegetables for commercial purposes, while a small percentage plant their crops for both commercial and subsistence.

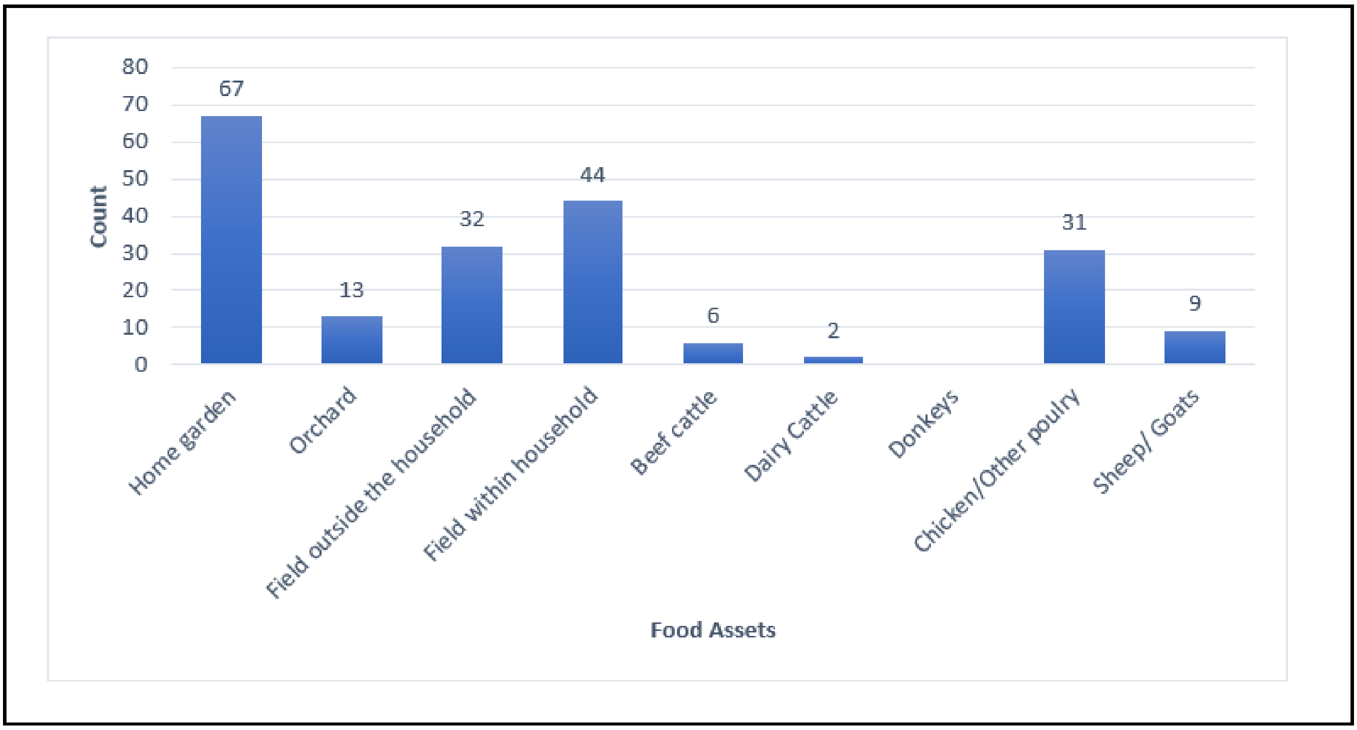

Figure 4.9: Food assets used at the household level

The study also identified that some of the respondents practice animal husbandry, wherein animals are raised for meat, milk, or to sell. About 33.3% (n= 31) practised poultry to produce meat and eggs. Only 8.6% (n= 8) of 93 respondents within the study area were found to own cattle, but only 6.5% (n= 6) of 8.6% practised cattle farming for meat and 2.1% (n= 2) kept the cattle for production of good quality and quantity of milk. The remaining 9.7% (n= 9) had sheep/goats.

Water is a critical input for agricultural production and plays a significant role in food security. Thus, respondents were asked about their views on the importance of water in crops (Figure 4.10). A total of 36.6% (n= 34) believed that water's importance in the growth of their products is low. This was because their farms or orchards depend on rain-fed irrigation, thus did not have to water their plants using the available water, while 37.6% (n= 35) agreed that water was important to crops because they grow their crops in areas equipped to provide water through artificial means of irrigation such as diverting streams, flooding and spraying. About 4.3% (n= 4) did not practice farming; hence, they had no views, while 9.7% (n= 9) responded “I don’t know”, and 11.8% (n= 11) did not specify their views.

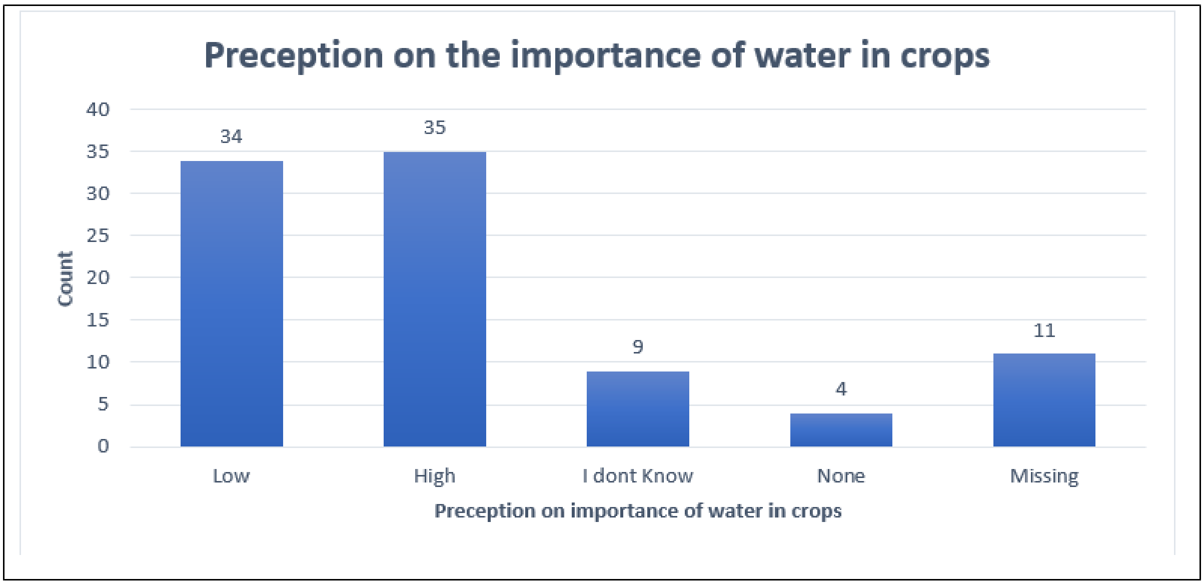

Figure 4.10: The perceptions on the importance of water in crops

According to 60.2% (n= 56) of the respondents, the importance of energy in crops is low, although modern agriculture requires an energy input at all stages of agricultural production (Figure 4.11). This was because they did not rely on machines for ploughing, nor did they have to pump water to irrigate their farms. Energy is needed in farm machinery, harvesting, and water pumping. Only 12.9% (n= 12) agreed that 10.8%, (n= 10), 4.3% (n= 4) did not practice crop farming energy is important in crops.

Those that indicated that they do not were found to be, and 11.8% (n= 11) did not specify their views as shown in Figure 4.11.

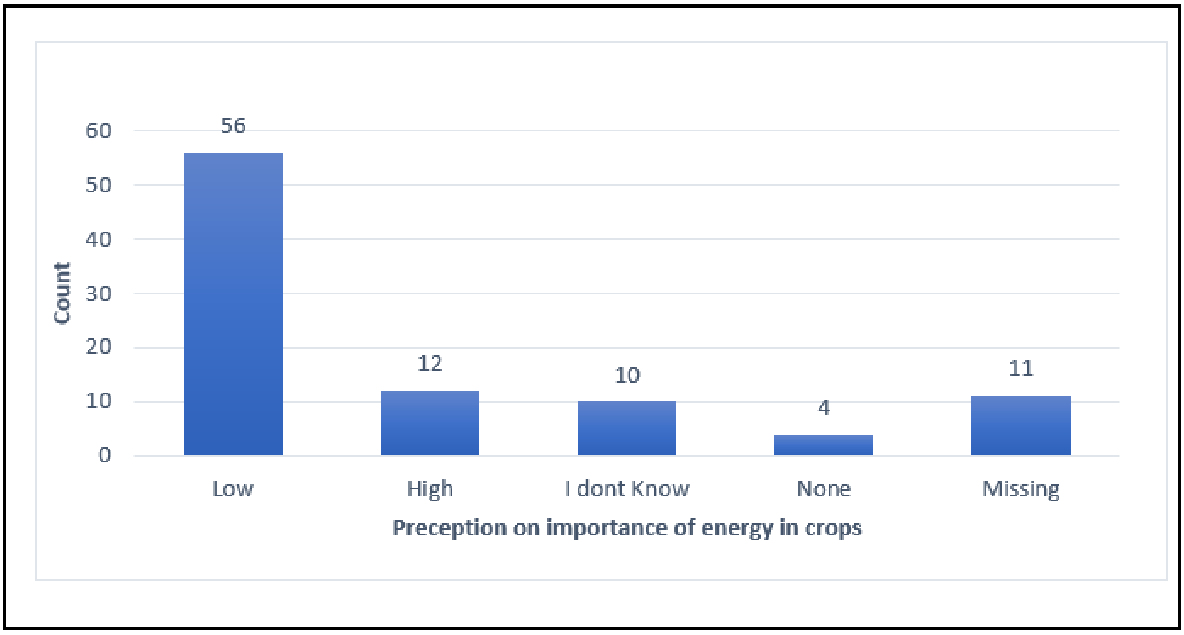

Figure 4.11: The perception of the importance of energy in crops in the study.

The majority (24.7%, n= 23) of the respondents practising livestock farming believed that water's importance in livestock is high (Figure 4.12). This is because animals need water to keep their bodies at a relatively stable temperature for digestion and absorption of feeds. About 11.8% (n= 11) responded that, according to them, the importance of water on livestock is low due to a lack of education and awareness on how to keep their animals in a good state of health. The remaining 62.4% (n= 58) did not practice livestock farming, whereas one respondent did not specify the perception of the importance of water in livestock.

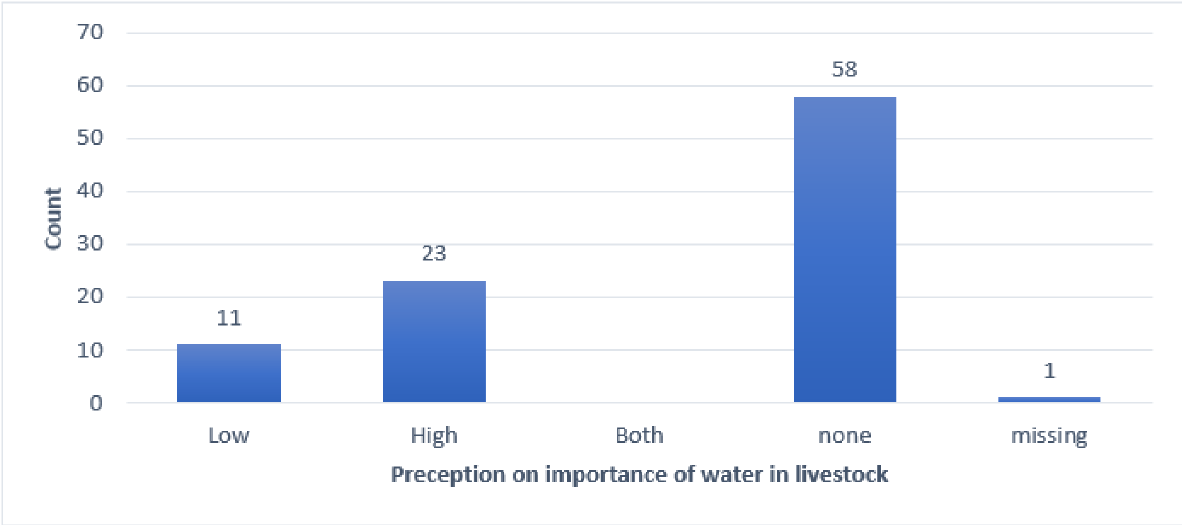

Figure 4.12:The perception of the importance of water in livestock in the study

When asked about the importance of energy in livestock, 28.0% (n= 26) indicated that the importance is low, 7.5% (n= 7) indicated that it was high, whereas 62.4% (n= 58) did not have any perception (Figure 4.13). The remaining respondents (1.1%, n= 1) did not specify the importance of energy in livestock. Those who stated that energy importance in livestock is high further explained that they use energy resources for lights within their farmhouses. Others reported using heaters during winter to keep their animals warm and comfortable, while some used diesel to transport their animals to feed lots. The results also showed that energy is important to those have cattle, who use electrical equipment to milk their cows. Those who did not see the importance of energy in livestock did not practice livestock farming, Figure 4.13.

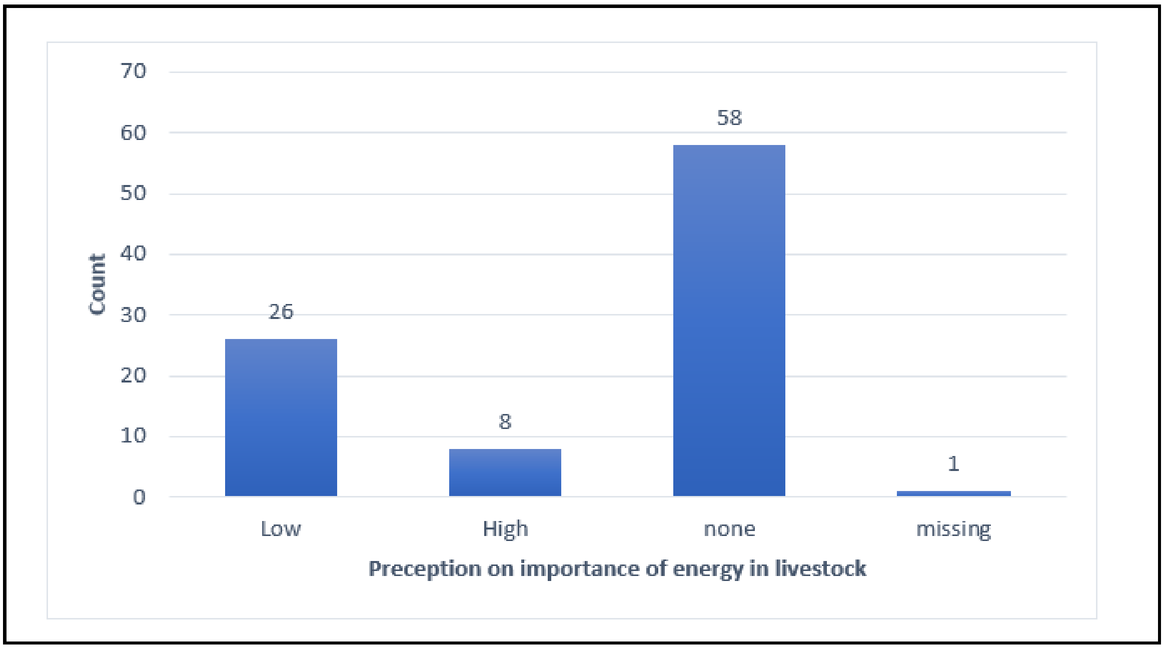

Figure 4.13: The perception of the importance of energy in livestock in the study

The study determined that respondents practise farming for different reasons. Some grow their crops and livestock to fulfil their families' needs, while others run agribusinesses where crops are produced and livestock are reared to sell the produce in the markets and gain profits. The study also found that most respondents are focused on practising subsistence farming, while others are practising both subsistence and commercial farming.

Figure 4.14 displays the use of irrigation systems in different levels of farming. Most of the respondents use buckets (n= 24), furrows (n= 2), sprinklers (n= 1), and drip irrigation systems (n= 1), respectively, in subsistence farming. This is because modern agricultural techniques and methods are less used in subsistence farming since the holding size is small. In addition, people mostly prefer manual labour and less water use. It is displayed in Table 4.6 that many of the respondents practicing subsistence farming believed that the importance of water and energy is practically low.

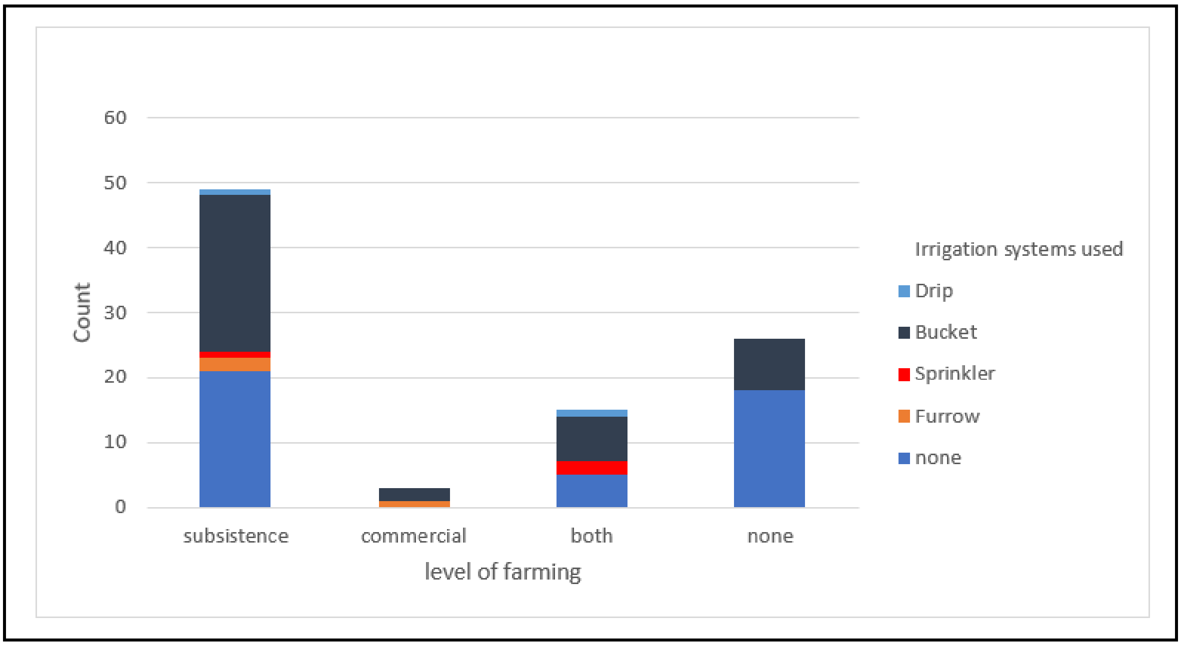

Figure 4.14: Commercial levels versus the type of irrigation systems being used.

Table 4.6: Level of commercial level vs the perception of the importance of energy/water in crops

		Level of commercial			
		Subsistence	**Commercial**	**Both**	**None**
		Count	Count	Count	Count
Perception of the importance of energy in crops	Low	41	3	9	3
	High	2	0	4	6
	I don't Know	1	0	1	8
	None	0	0	0	4
	Missing	5	0	1	5
		Level of commercial			
		Subsistence	**Commercial**	**Both**	**None**
		Count	Count	Count	Count
Perception on the importance of water in crops	Low	27	0	3	4
	High	16	3	11	5
	I don't Know	1	0	0	8
	None	0	0	0	4
	Missing	5	0	1	5

Only a minor percentage of those practising commercial farming irrigate their crops using buckets (2.2%, n= 2) and furrows (1.1%, n= 1). This is because it is mostly practised in a large area, enhanced through higher doses of modern inputs, and depends on rainfed irrigation. The remaining respondents practice both commercial and subsistence farming, wherein five respondents do not irrigate, and the remaining seven irrigate using buckets because their gardens are small and not from the farms and orchards. The results further showed that two respondents used sprinkles and one used drip to irrigate.

4.5 Marketing channels that are used in the study area

Marketing is an integral component of agriculture, encompassing critical post-production activities such as packaging, preservation, storage, processing, and advertisement of agricultural products, all essential for connecting producers with consumers. The respondents in this study who are engaged in farming provided insights into the marketing channels they utilize, revealing patterns with significant implications for their income, market integration, and importantly, their adoption of agricultural innovations and practices.

The data presented in Table 4.7 indicates that a substantial majority of farmers engaged in crop production (53.8%, n=68) and an even larger proportion of those in livestock farming (82.8%, n=77) reported using no formal marketing channels. This striking finding suggests that a significant portion of agricultural activity in the study area may be primarily for subsistence, with produce largely consumed at the household level. The significance of this is profound: without access to or engagement with markets, farmers have limited avenues to generate income from their agricultural activities, which in turn can dampen the incentive to adopt innovations aimed at increasing yield beyond household needs or improving product quality for specific market demands. Consequently, adoption behaviours in this large segment are likely geared towards risk aversion, household food security, and resilience, rather than commercial optimization or investment in potentially costly productivity-enhancing technologies. This lack of market engagement can also lead to isolation from crucial market information, price signals, and quality requirements that often drive innovation adoption in more commercialized settings.

Table 4.7: Marketing channels used in the study area.

Marketing channels for crops			
	Frequency	Per cent	Cumulative Percent
Farmgate	18	19.4	19.4
Vendor	3	3.2	22.6
Official channel (boxer. spar)	4	4.3	26.9
None	68	53.8	100.0
Total	93	100.0	
Marketing channels for livestock			
Farmgate	15	16.1	16.1
Official channel (boxer. spar)	1	1.1	17.2
None	77	82.8	100.0
Total	93	100.0	

For those crop farmers who do market their produce, Farmgate sales emerge as the most common channel (19.4%, n=18). These farmers typically rely on informal promotional methods such as word-of-mouth, posters, and increasingly, social media to attract local buyers directly to their farms. The significance of this approach lies in its low transaction costs for farmers (e.g., minimal transportation expenses) and direct interaction with consumers. However, it also means sales are often limited by local demand, potentially leading to lower prices compared to formal markets, and increased risk of spoilage if sales are slow. In terms of adoption behaviour, farmgate sales might encourage the adoption of practices that cater to immediate, local consumer preferences and small-scale, low-cost innovations for managing small surpluses. The use of social media itself represents an adoption of a modern communication technology for marketing purposes, albeit for a very localized market.

Those few farmers (4.3%) accessing official channels are likely more commercially oriented and have already adopted many of these requisite practices and technologies.

The situation is even more challenging for livestock farmers, where only 16.1% (n=15) use Farmgate sales and a mere 1.1% (n=1) access official channels. The overwhelming reliance on "none" (82.8%) for marketing underscores the substantial hurdles in this sub-sector. As noted, livestock farmers face numerous marketing challenges, and a lack of awareness or access to channels such as auctions, abattoirs, speculators, or formal butcheries severely restricts their commercial potential. This limited market access likely hinders the adoption of improved animal husbandry practices, including enhanced breeding techniques, comprehensive animal health protocols, and advanced feed technologies, as the financial returns on such investments cannot be easily realized without reliable and profitable market outlets. The suggestion that commercial cattle farmers should understand channels like auctions and butcheries implies that adopting a commercial farming orientation is intrinsically linked to adopting these more formal marketing pathways and the associated best practices.

The marketing channels (or lack thereof) utilized by farmers in the study area have a profound significance for their economic outcomes and are intricately linked to their adoption behaviours. The predominance of subsistence farming or highly localized, informal sales channels for a majority of respondents suggests limited exposure and incentive to adopt market-driven innovations. Conversely, the ability to access more formal and demanding markets, though limited to a small fraction, necessitates and rewards the adoption of a suite of improved technologies and practices. Therefore, any efforts to promote WEF nexus smart innovations and technologies, particularly those aimed at enhancing productivity and commercialization (as alluded to by Rabadan et al., 2021, regarding meeting demand with improved and sustainable food alternatives), must concurrently address the fundamental constraints in market access and develop marketing channels that are inclusive and accessible to smallholder farmers. Enhancing marketing opportunities could, in turn, become a significant catalyst for the wider adoption of beneficial agricultural practices, including those related to conservation agriculture, smart irrigation, and sustainable intensification.

Table 4.8 shows the food processing, preservation and storage methods which were being used in the study area. Food processing methods are crucial in agricultural farming as they ensure that fresh foods are turned into food products through various traditional and modern processing methods. When asked about the type of processing methods they use, most of the respondents (58.1%; n= 54) in crop farming responded “local harmer milling” to process their maize into maize meals (Table 4.8). After processing the maize meals from their farms, others sell them in different-sized bags while others use them to feed their families instead of buying. The remaining respondents use freezing (6.5%; n= 6) and smoking (3.2%; n= 3) as processing methods wherein meat is heated by exposing it to smoke from burning materials such as wood and freezing food in reduced temperatures below 0°C to decrease harmful bacteria.

The study determined that 40.9% (n= 38) of the respondents use sun drying to preserve their produce. They pre-cook their vegetables or meat then expose the produce to the sun and leave it to dry to help preserve it for a particular period. Another proportion (24.7%, n= 23) is of those using freezers. Respondents stated that it becomes easier to slaughter meat in bulk, store it in freezers, and then sell it as buyers come (Table 4.8). The results showed that 8.6% (n= 8) were using pills as a preservation method wherein a measurable amount of pills is inserted inside the bins or sacs that they use at their households after harvesting corn; this is done to treat and prevent maize insect damage. The remaining percentage 1.1% (n= 1), 1.1% (n= 1), 3.3% (n= 3) of the respondents use salting, blanching and fermentation, respectively.

Table 4.8: Food processing, preservation and storage methods used in the study area.

Food processing methods			
	Frequency	**Per cent**	**Cumulative Percent**
Hammer Milling locally	54	58.1	58.1
Freezing	6	6.5	64.5
Smoking	3	3.2	67.7
None	30	32.3	100.0
Total	**93**	**100.0**	
Food preservation methods			
	Frequency	**Per cent**	**Cumulative Percent**
Sun drying	38	40.9	40.9
Pills (Fumigation)	8	8.6	49.5
Blanching	1	1.1	50.5
Salting	1	1.1	72.0
Fermentation	3	3.2	75.3
freezer/fridge	23	24.7	100.0
None	19	20.4	71.0
Total	**93**	**100.0**	
Food storage methods			
	Frequency	**Per cent**	**Cumulative Percent**
Traditional grain bin	2	2.2	2.2
Mud Bin	2	2.2	4.3
Congregated Steel House	3	3.2	7.5
Drums	6	6.5	14.0
Spare room	11	11.8	25.8
freezer	21	22.6	48.4
Sacs	28	30.1	78.5
None	20	16.1	94.6
Total	**93**	**100.0**	

The respondents stated sacks (30.1%; n= 28); freezers (22.6%, n= 21) and spare rooms (11.8%, n= 11) as the methods used to store their post-products to ensure that food is available all seasons of the year (Table 4.8). In addition, this method is used to reduce food spoilage, take advantage of higher prices during the off-season, and ensure an adequate supply of raw materials to buyers. Those in crop farming further indicated that they use grain bins (2.2%, n= 2), mud bins (2.2%, n= 2) and drums (6.5%, n= 6) to store their post-harvest crops. Those who responded "none" stated that they harvest and sell without storing their produce.

Rabadan *et al*. (2021) stated that the current demand for healthy and sustainable foods has encouraged the development of new alternatives, even in traditional products. Improved foods may be produced by reducing the amount of some ingredients, adding new ones, or replacing traditionally used ingredients with others. Thus, to meet the population's demand for food, more food needs to be produced, encouraging the development of smart and nutrition-sensitive innovations and technologies. This further highlights the importance of the findings of the current study. As such, this study investigated the use of food innovation, technologies and practices at the household level. Conservation agriculture (CA), smart irrigation (SI), sustainable intensification (SINT), disaster Intervention (DI) and behaviour change interventions (BI), which are components of agricultural practices, were investigated (Table 4.9). Food-related smart technologies, innovation and practices refer to various ways in which technology and innovative approaches are applied to improve food-related activities such as food production. Examples include the use of drips, sprinkles and farrows to irrigate.

Table 4.9: Food innovations, technologies and practices that are used at the study area (n= 93)

Food-related Innovations, technologies and practices										
	Conservation agriculture (CA)	*f*	Smart irrigation (SI)	*f*	Sustainable intensification (SINT)	*f*	Disaster Intervention (DI)		Behaviour changes interventions (BI)	*f*
	Total number of respondents using CA	40	Total number of respondents using SI	05	Total number of respondents using SINT	11	Total number of respondents using DI	01	Total number of respondents using BI	08
Type of innovation technology and practices used	Zero tillage	2	Drip irrigation	3	Relay cropping	4	Reporting to the chief	1	Membership in innovation platform (IP)	8
	Mulching	30	Sprinkles	1	Fallowing	4			Receives Agriculture training (Field days. Tours	8
	Manure	12	Buckets	1	Agroforestry	2			Receives regular agriculture advisories other than fielders/ demos	4
					Organic practices	4				
Reasons for using innovation technology and practices	Conserve soil moisture	4	Reduced cost of irrigation system	1	Awareness on advantages	3	Preventing conflicts	1		
	Premium prices for production	2								
	High cost of commercial inputs	5			Increased output (crop yield)	4				
	Concern for the Environment	3	Uses less Water	4	Soil fertility improvement	4				
	Replenish soil fertility.	26								
Challenges	High labour intensity	9	Blocking of nozzles	4	Difficult to use in drought seasons	4	Lack of awareness	1		
	Pest	16	Labour intensive	1	High labour intensity	1				
	Costly	3			Pests	1				
	None	11			None	6				
Innovation technology ranking	Extremely poor	2	Extremely poor	0	Extremely poor		Extremely poor	1	Extremely poor	2
	Very poor	2	Very poor	0	Very poor	3	Very poor	0	Very poor	0
	Poor	11	Poor	0	Poor	2	Poor	0	Poor	0
	Good	11	Good	1	Good	6	Good	0	Good	3
	Excellent	15	Excellent	4	Excellent	1	Excellent	0	Excellent	3
	Missing	0	Missing	0	Missing	0	Missing	0	Missing	

The number of respondents using CA was found to be 43.0% (n= 40), wherein they were using it in the form of zero tillage (5%, n= 2), mulching (75%, n= 30) and manure (30%, n= 12). The respondents indicated their reasons for practising CA include replenishing soil fertility (65%, n= 26), conserving soil moisture (10%, (n= 4) and because of the high cost of commercial inputs (12.5%, n= 5). Minor percentages of (2.2%, n= 2) and (3.2%, n= 3) were of those who indicated that they are practising CA because of premium prices for production and the concern for the environment, respectively. The respondents further explained that they use CA to promote minimum soil disturbance and the maintenance of permanent soil cover, thus enhancing biodiversity.

The respondents who reported that using CA comes with a challenge of pests were found to be 40% (n= 16). Unlike other traditional weed and pest control methods, conservation tillage demands more pesticides and herbicides. The remaining respondents stated high labour intensity (22.5%, n= 9) and high costs (7.5%, n= 3) as a challenge (Table 4.9). This is because CA requires expensive equipment when used on a large farm or a lot of manual labour on small farms. Moreover, 11.8% (n= 11) of the respondents did not have challenges with using CA. Most respondents rated CA to be excellent (16.1%, n= 15), while some rated it very poor (2.1%, n= 2).

Out of the total number of 93 respondents, only 5.4% (n= 5) were using SI, of which 60% (n= 3) were using it in the form of a drip irrigation system, while the remaining were using sprinklers (n= 1) and buckets (n= 1). When asked why they are using SI, 80% (n= 4) reported using this type of agricultural-related innovation because it conserves water. The remaining percentage (1.1%, n= 1) responded to the irrigation system's reduced cost as a reason for using SI. Blocking of nozzles was found to be the major challenge of using sprinklers and drip irrigation. Clogging can occur if the water is not properly filtered and the equipment is not properly maintained. Respondents who rated SI as excellent were found to be 80% (n= 4) then the remaining n= 1 rated it as a good innovation system (Table 4.9).

The results showed that 11.8% (n= 11) of the total respondents were practising SINT, wherein relay cropping (36.4%; n= 4), fallowing (36.4%; n= 4), organic practices (36.4%; n= 4) and agroforestry (18.2%; n= 2) were practised (Table 4.9). The SINT aims to increase agricultural output from the same available land area while reducing the negative environmental impacts of agricultural technology. The respondents are utilising this agriculture-related innovation, technology/practice because they are aware of its advantages, while some are using it because of soil fertility improvement (36.4%; n= 4) and it increases crop yield (9.1%; n= 1).

When asked about the challenges of using SINT, most of the respondents (36.4%; n= 4) reported that it is difficult to use in drought seasons, while others stated high labour intensity and pests as challenges. Moreover, 54.5% (n= 6) had no challenges about using SINT innovation. The respondents rated this innovative technology as Good (n= 6), excellent (n= 1), very poor (n= 3), and poor (n= 2).

Only one respondent was found to be using DI agriculture. The DI was used as a management tool to prevent conflicts by reporting crimes to the local chief. When asked about the challenge, the respondent stated lack of awareness as a major concern. This innovative technology was rated extremely poor. Most farmers reported a lack of access to information on DI and how to practice it. The study also determined that villagers must be educated about this innovative technology.

Behaviour change interventions (BI) were used by 8.6% (n= 8) of the total respondents. All the respondents were found to have membership in an innovation platform (IP), received agricultural training (field days (tours)), and only 50% (n= 4) of the respondents practising BI received regular agriculture advisories other than fielders/ demos. This practice was rated as excellent (n= 3), good (n= 3) and poor (n= 2) (Table 4.9).

Figure 4.15 depicts the various influences on the adoption of food innovations, technologies and practices, where multiple responses were permitted since various factors influenced respondents. Those who stated that knowledge, reliability, value for the environment and cost saving influenced their use of food innovations, technologies and practices were found to be 49.5% (n= 46), 37.6% (n= 35), 33.3% (n= 31) and 30.1% (n= 28), respectively. Food innovations, technologies and practices have proven to improve environmental quality. Other respondents who stated grants, incentives, free input, family spillovers and rebates as factors influencing them to use food innovations were found to be 20.4% (n= 19), 4.3% (n= 4), 2.1% (n= 2), 7.5% (n= 7), and 1.1% (n= 1), respectively.

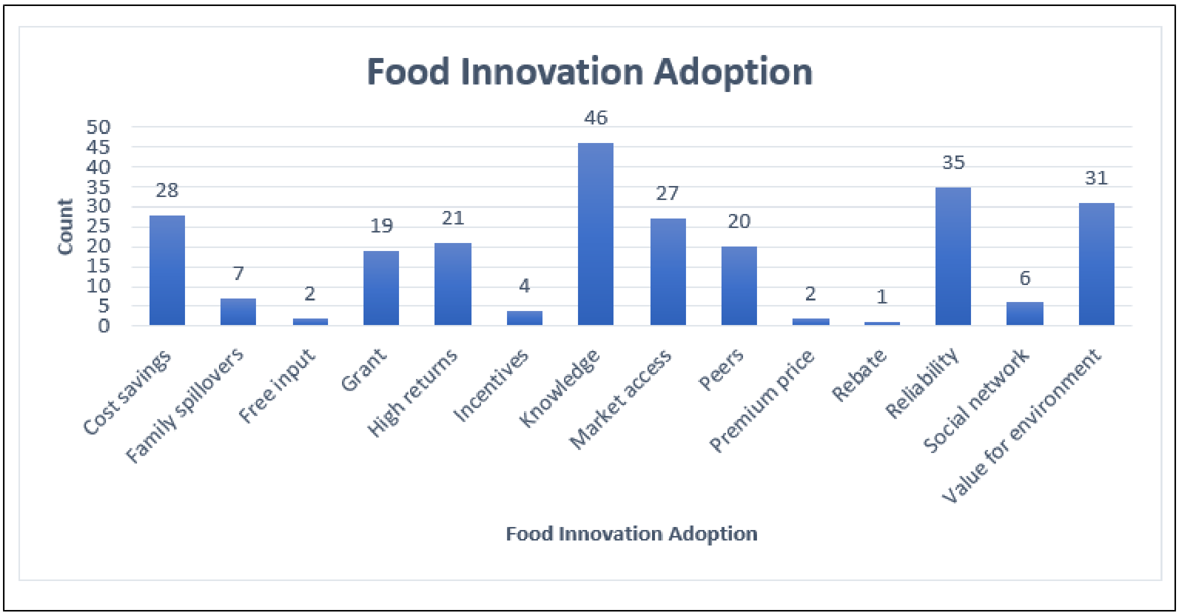

Figure 4.15: Factors affecting the influence of respondent's adoption to food innovation technologies

4.6 Chapter Summary

This chapter presented the results for the identification of WEF nexus smart innovations, technologies, and practices within the study area. Demographic characteristics and socio-economic conditions on the adoption and accessibility of WEF innovations, technologies, and practices. The chapter further investigated the type of innovation technology used, its uses, challenges, and reasons for using such an innovation technology.

CHAPTER 5: COMPARISON OF INNOVATIONS, TECHNOLOGIES AND PRACTICES IN THE STUDY AREA

5.1 Preamble

This chapter presented findings and a discussion on the comparison of innovations, technologies, and practices between the two study areas, which were obtained from GIS. The thematic maps produced for each innovation are also presented here. This chapter further presented pictures taken during the field survey.

5.2 Inverse distance weighting (IDW) spatial interpolation results for water, non-renewable energy and food innovations

Figure 5.1 illustrates the variations in water practices among six distinct villages in the research locations. When asked to list the water-related innovations, technologies and practices employed in their villages, respondents indicated that most of these innovations, technologies and practices were used for groundwater, rainwater, water recycling, and water loss reduction. The IDW interpolation findings are shown in Figure 5.1, which depicts a map with the differences between these water sources and practices. Red denotes areas with a high percentage of respondents employing a particular innovation, while blue denotes areas with a low percentage.

Respondents from Tshakhuma, Sambandou and Khalavha were likelier to use rainwater than those from Phadzima, Siloam, and Malavuwe (Figure 5.1). The respondents indicated that even if they agreed to adopt these innovations, technologies, and practices, they would do so in diverse ways and for various reasons. Only eight of the respondents in Siloam and six in Malavuwe agreed to use rainwater, according to the data shown in Appendix B. This demonstrated that while rainwater is available in the village, only a few residents possess enough knowledge to use it more innovatively.

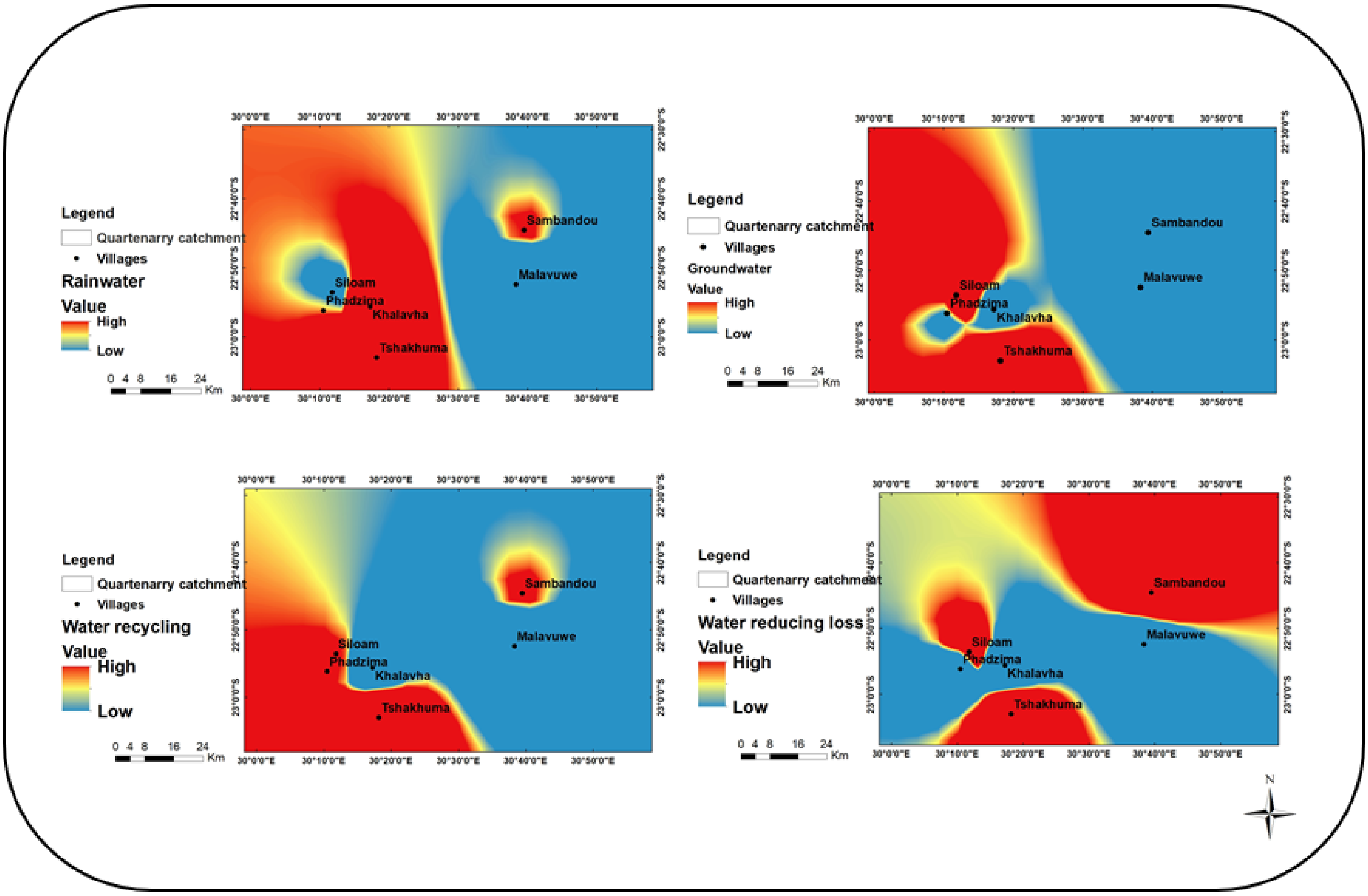

Figure 5.1: IDW spatial interpolation for the differences/similarities in water practices

In contrast to the other villages, Tshakhuma and Siloam have a high percentage of respondents who use groundwater as a source of water (Figure 5.1; Appendix B). Furthermore, it was discovered that water recycling was practised in every village, except Malavuwe and Khalavha, where a high percentage of respondents said they used water recycling. It was noted that fewer respondents in Malavuwe and Khalavha agreed to use water-smart innovations, technologies and practices, so educating the local population in this area is essential.

The higher prevalence of rainwater harvesting in Tshakhuma, Sambandou, and Khalavha may suggest a stronger presence of local initiatives, historical coping strategies for water scarcity, or perhaps poorer municipal water reliability that necessitates such alternatives. Conversely, the high reliance on groundwater in

Tshakhuma and Siloam, while providing a crucial water source, raises significant sustainability concerns regarding aquifer depletion if not properly managed.

The spatial disparity strongly suggests that a one-size-fits-all approach to water management will be ineffective. The low adoption of rainwater harvesting in Phadzima, Siloam, and Malavuwe points to a critical need for targeted interventions. Policymakers should focus on awareness campaigns and financial support, such as subsidies for rainwater harvesting tanks, specifically in these "cold spots" of adoption. In areas with high groundwater dependency like Tshakhuma and Siloam, the priority must be on establishing community-based or municipal-level groundwater monitoring programs to track water levels and ensure sustainable abstraction rates, coupled with promoting water conservation and recharge technologies. Pictures of some of the water innovations and practices used in the study area are shown in Figure 5.2.

Figure 5.2: Water innovations, technologies and practices

According to Figure 5.3, electricity and firewood were the most common sources of energy used in these villages, as almost 98% of the respondents agreed to using both electricity and firewood as their main source of energy, as shown in Appendix C. Those who were not using electricity stated that it was because electricity had not been installed within their households. The number of people using electricity was higher in Siloam, Phadzima and Malavuwe (Figure 5.3). At Sambandou, Khalavha and Tshakhuma, the use of electricity was low. Electricity alone may not be able to create all the conditions for socio-economic growth, but it is essential for basic human needs, and access to electricity can improve conditions in these villages that have no access to electricity av   s there is a strong correlation that exists between rural poverty and access to electricity because electricity is a pre-requisite for productive activities. (Kirubi et al., 2009).

Another similarity that exists between these villages is the use of firewood. Most of the respondents agreed to using firewood as an alternative to the expense of electricity as well as loadshedding while those who did not have electricity used firewood for household essentials such as cooking, heating and lightning. A few of the respondents who were using paraffin were using it in the form of paraffin lights and stoves, which was found to be common in Phadzima, Malavuwe and Sambandou. An example of the use of paraffin in Phadzima, Malavuwe and Sambandou is shown in Figure 5.5. Solid fuels are predominantly used in these areas as most households are non-electrified. However, a low percentage of households use coal as a main energy source; therefore, coal was only used in Siloam and Tshakhuma.

The energy landscape depicted in Figure 5.3 and Figure 5.4 reveals a complex and underdeveloped energy system, caught between reliance on traditional, often unsustainable sources and the slow, challenging adoption of modern renewable innovations. A deeper analysis of this dynamic is crucial for understanding the realities of energy transition in this local context.

The current energy mix is dominated by two primary sources: grid electricity and traditional biomass (firewood). While nearly all respondents use firewood, access to grid electricity is spatially inconsistent, with lower usage in Sambandou, Khalavha, and Tshakhuma. This highlights a foundational challenge of energy poverty. Grid electricity, as noted by Kirubi *et al*. (2009), is a prerequisite for many productive activities and improving basic human needs. However, even where the grid is present, its unreliability (due to loadshedding) and the cost of connection and consumption force households to maintain a heavy reliance on firewood. This creates a challenging baseline for any energy transition.

The widespread use of firewood and other solid fuels is not merely a matter of preference but one of necessity, driven by poverty and energy insecurity. This reliance has profound and unsustainable implications. Environmentally, it contributes to local deforestation and land degradation. From a health perspective, it exposes households, particularly women and children, to harmful indoor air pollution. Socio-economically, it imposes a significant time and labour burden for fuel collection.

Against this backdrop, renewable energy innovations like solar and biogas represent a critical pathway toward a more sustainable and equitable energy future. Their decentralized nature is perfectly suited to addressing energy access gaps in rural areas, providing resilience during grid outages, and mitigating the negative health and environmental impacts of solid fuels. However, their adoption is minimal. The study found that the primary barrier to adopting solar energy, despite awareness of its benefits, is the high initial cost. This single factor is the central conflict in the local energy transition. While biogas offers a viable alternative for cooking, especially when firewood is scarce, its use was negligible, suggesting similar barriers related to cost, technical knowledge, or cultural acceptance.

The findings suggest that the challenge is not simply a transition from fossil fuels to renewables on a national scale, but a household-level struggle to move up the energy ladder. A successful energy transition in this context must address the immediate realities of energy poverty and the trade-offs households are forced to make. Policymakers must move beyond general awareness campaigns for renewables. To overcome the critical barrier of high initial costs, targeted financial instruments are essential. This could include government-backed microfinance loans, rent-to-own schemes for solar home systems, or direct subsidies for the construction of biogas digesters. Furthermore, fostering community-based energy models or supporting local entrepreneurs to provide and service renewable energy technologies could create sustainable local ecosystems for clean energy. This approach addresses the affordability and access barriers simultaneously, creating a viable pathway for households to transition away from the unsustainable reliance on firewood and towards a more secure and sustainable energy future.

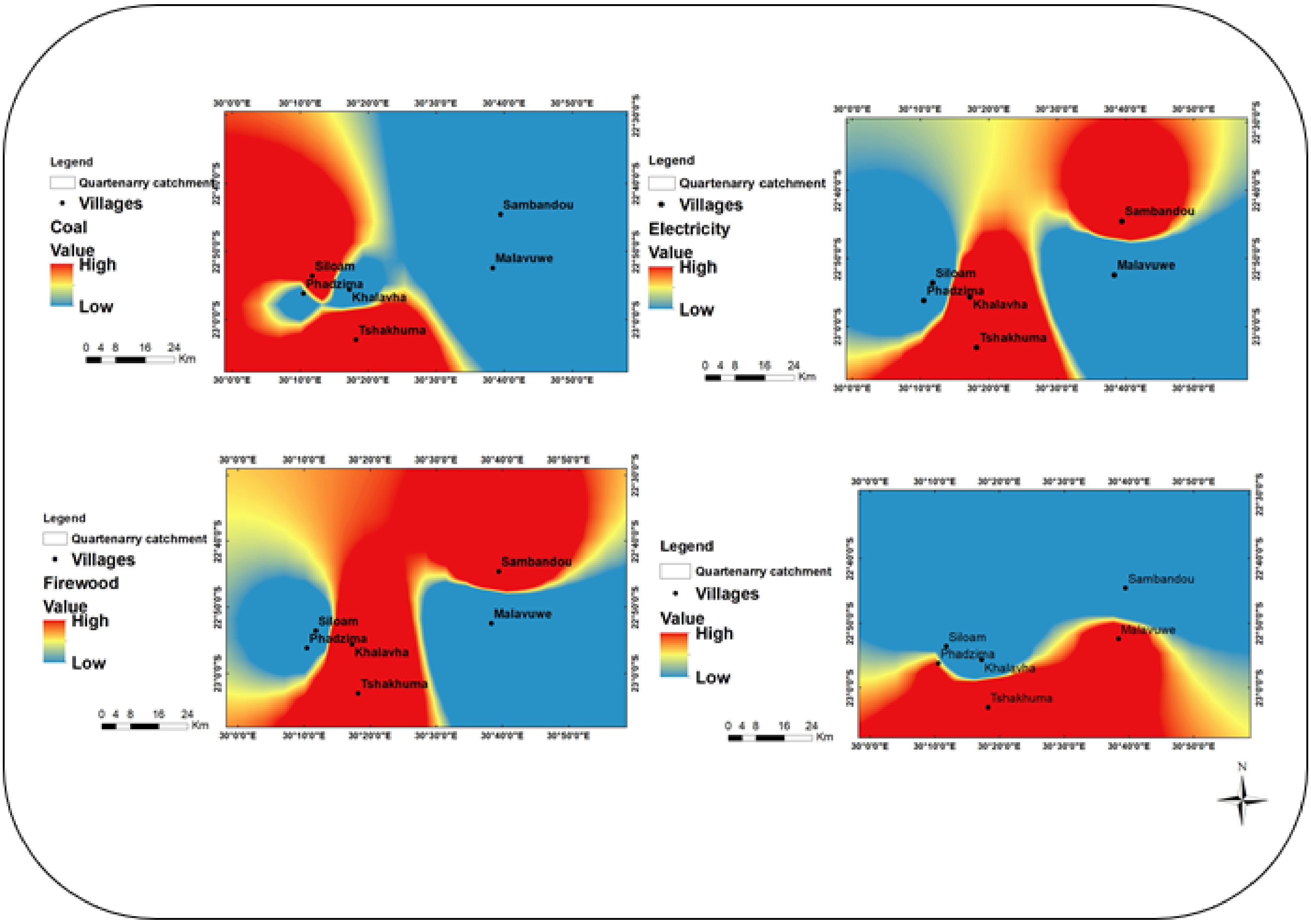

Figure 5.3: IDW spatial interpolation for the differences/similarities in energy practices

5.3 Inverse distance weighting (IDW) spatial analytical interpolation results for renewable energy innovation

Adopting solar energy in rural areas can reduce the use of fossil fuels and result in the use of cheap energy. Furthermore, many social and economic benefits are connected to solar installations in these rural areas. Regardless of the positive impacts of solar energy, only a few respondents from Siloam, Phadzima and Tshakhuma (Figure 5.4) were found to be using solar energy as their energy source. However, the study determined that the reason was not because they did not have information on the use of solar, but they stated that it was because of high initial costs. Solar energy is utilised through solar lamps and solar water heaters.

As some of the households do not have electricity, biogas is being used for cooking in these low-income households during rainy days, when the use of firewood is not favourable. Though using biogas is a good alternative, only two villages used it, Malavuwe and Tshakhuma. Wind energy was not used in any of the villages within the study area.

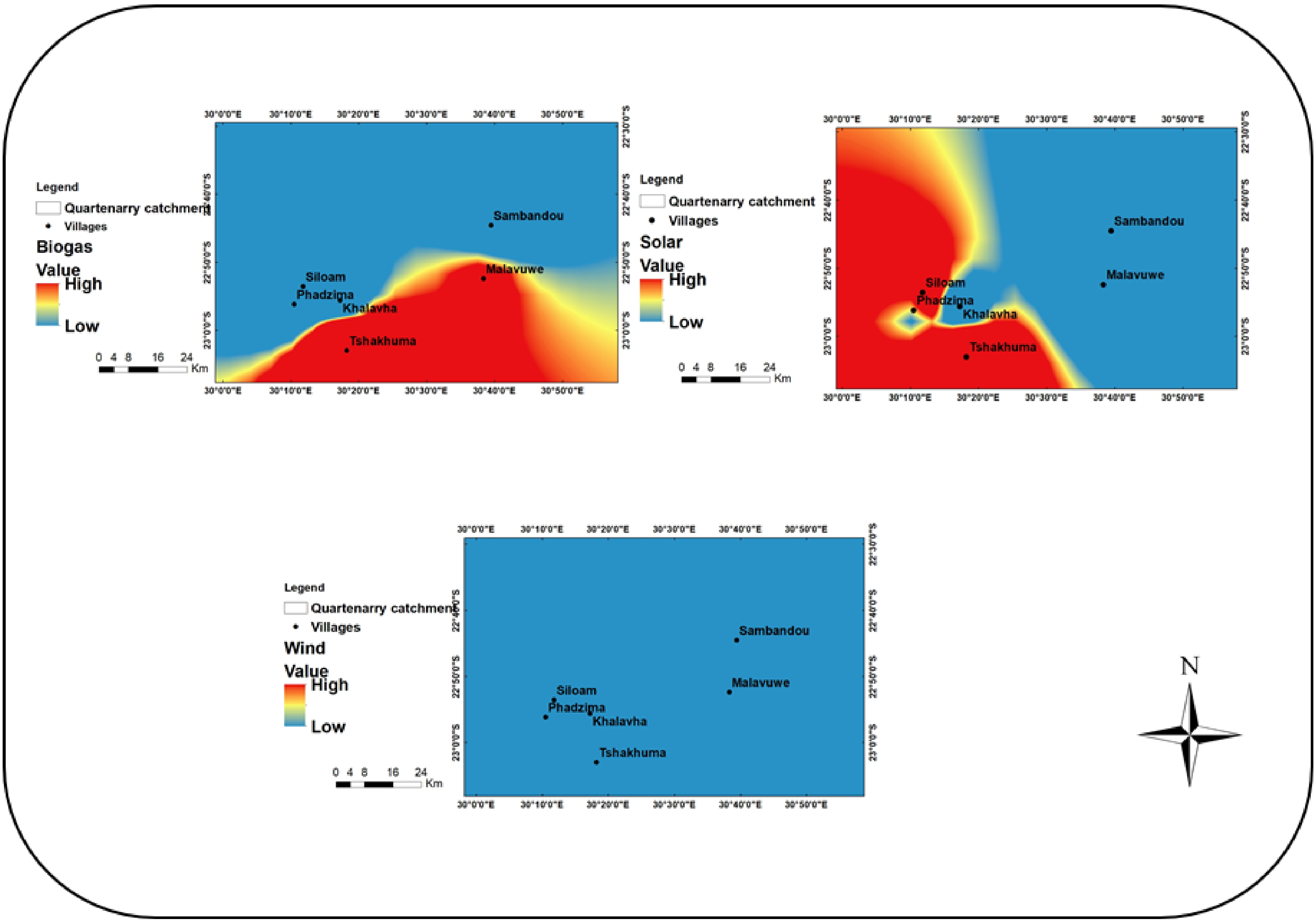

Figure 5.4: IDW spatial interpolation for the differences/similarities in renewable energy practices

Figure 5.5: Energy innovations, technologies and practices

5.4 Inverse distance weighting (IDW) spatial analytical interpolation results for food innovations

Figure 5.6 shows the spatial comparison of food innovations used within the study area. Villages within the study area depend mostly on agricultural production, which alleviates poverty and creates more job opportunities. Although commercial farming is practised in these areas, subsistence farming takes the lead. It is cost-effective as compared to large-scale farming. Implementing CA is imperative as the villages in question are found in a region with low rainfall, limited agricultural lands, and a large smallholder farming community. The use of CA is very common within the study area for both subsistence and commercial farming it generally had a positive effect on soil properties and crop yield. Respondents from Siloam, Phadzima and Khalavha understood the use of drip irrigation in their fields or backyards as they argued that it saves water while delivering water directly to the roots. In contrast, the other three villages did not practice drip irrigation.

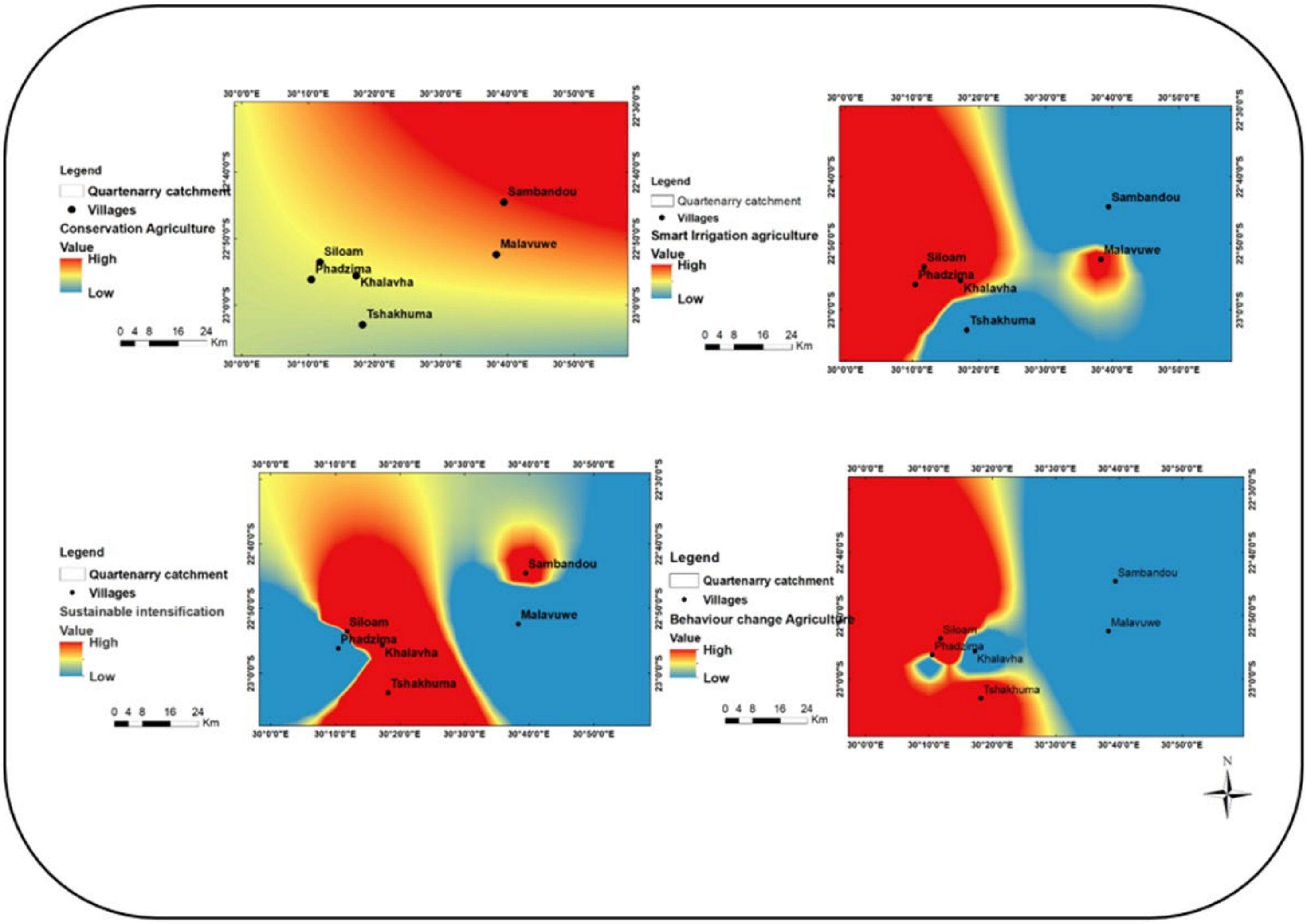

Figure 5.6: IDW spatial interpolation for the differences/similarities in renewable energy innovations

In agriculture, behaviour change interventions improve health outcomes by promoting positive behaviours to improve feeding practices and reduce losses. Sambandou and Tshakhuma practice BI in nutrition education, providing information and skills to farmers on producing processed nutritious foods. Only a few respondents agreed to have knowledge about sustainable intensification agriculture, while even fewer were practising it. This shows that most of the respondents are not knowledgeable about most of the smart innovations they can use for sustainable agricultural practices; thus, there is a need for awareness.

Figure 5.6 similarly uncovers an uneven landscape of agricultural innovation. The concentration of drip irrigation knowledge and use in Siloam, Phadzima, and Khalavha indicates that access to water-saving technologies and the associated extension services is not uniform. The same applies to Behavioural Interventions (BI) in nutrition, which appear localized to Sambandou and Tshakhuma, likely due to a targeted health or agricultural program.

This patchiness in adoption creates disparities in farm productivity, climate resilience, and potential income. Practitioners, such as agricultural extension officers, should use these spatial findings to identify and prioritize villages where knowledge and technology gaps are most apparent. Successful initiatives, like the BI nutrition program in Sambandou and Tshakhuma, should be studied as models of best practice that could be scaled up or replicated in neighboring communities to broaden their impact. Some of the practices and innovations being utilised are shown in Figure 5.7.

Figure 5.7: Food innovations, technologies and practices

5.5 Cross-Sectoral Analysis of Innovation Adoption

A cross-sectoral analysis of the IDW spatial interpolation maps revealed a significant patterns and potential interlinkages that underscore the value of the WEF nexus framework. By comparing adoption behaviours across water, energy, and food innovations, it is possible to identify village-level hotspots and coldspots of innovation, suggesting underlying systemic factors that either enable or constrain sustainable development.

Some of the villages within the study area emerged as more progressive in adopting innovations across multiple sectors. Tshakhuma, for example, demonstrated higher adoption of rainwater harvesting, groundwater use, some renewable energy (solar), and practices nutrition-focused Behavioural Interventions (BI). Similarly, Siloam showed high uptake of groundwater use and water-saving drip irrigation. This clustering of innovations suggests that these villages may possess enabling characteristics such as higher levels of social capital, more effective local leadership, better access to information and extension services, or a stronger market orientation that justifies investment in new technologies. The co-location of high groundwater use and drip irrigation adoption in Siloam points to a direct WEF nexus synergy: as communities rely on an energy-intensive water source which is pumped groundwater. They are also adopting water-efficient (and thus energy-saving) agricultural technologies.

Conversely, some villages exhibit consistently lower adoption rates, indicating systemic barriers. Malavuwe, for instance, showed low adoption of rainwater harvesting and was one of the villages with lower electricity usage, suggesting potential exclusion in terms of both infrastructure and access to alternative technologies. The low uptake of multiple smart innovations in certain areas signals that challenges are not isolated to a single sector. For example, a lack of reliable and affordable energy can directly hinder the adoption of modern water technologies that require pumping such as advanced irrigation and food processing technologies such as refrigeration or milling, thereby suppressing agricultural development.

This cross-sectoral view confirms that innovation adoption is not random; it is spatially concentrated and systemically linked. Addressing a single sectoral issue in isolation—such as promoting water technologies without considering energy access—is likely to have limited success. A coherent nexus approach, therefore, required identifying these patterns to design bundled interventions that address interlinked challenges simultaneously.

5.5 Spatial differences in adoption rates

The spatial differences in innovation adoption revealed by the IDW maps are unlikely to be spontaneous. They point towards underlying socio-economic, infrastructural, and political factors that shape the capacity and willingness of communities and individuals to adopt new practices. Understanding these drivers is critical for designing equitable and effective policies.

It is probable that villages with higher adoption rates, such as Tshakhuma and Siloam, have higher average household incomes or greater income diversity, providing the necessary capital to invest in innovations like solar panels or drip irrigation systems. Education levels and access to information also play a crucial role; higher literacy may correlate with a greater ability to understand and implement technical instructions for new practices. The presence of experienced farmers or influential community leaders who successfully adopt an innovation can create a powerful demonstration effect, accelerating diffusion through social networks.

The physical infrastructure available to a village is a key determinant of its development trajectory. Villages with better road access are more connected to markets, suppliers, and information from nearby towns. The stark differences in grid electricity usage, for example, are a direct reflection of infrastructural reach. Villages with poor grid coverage are immediately disadvantaged in adopting all innovations that require electricity. Similarly, reliable mobile network coverage can influence access to information, social media marketing for farmgate sales, and coordination among farmers. The presence of local non-governmental organization (NGO) offices or government extension services can also create innovation hotspots by providing sustained technical and financial support.

The role of local governance, both formal and traditional, cannot be overstated. An active and supportive traditional leader (chief) or a proactive local councillor can be instrumental in mobilising community support for development projects and facilitating access to government programs. The history of past interventions also matters; a legacy of successful projects can build community trust and openness to new ideas, while failed initiatives can breed skepticism and resistance. Therefore, the observed spatial disparities may reflect differing levels of institutional effectiveness and community trust in external actors and new initiatives.

5.6 Chapter summary

This chapter presented the mapped and quantified similarities/differences in the study area's innovations, technologies and practices. Although some similarities exist within these villages, areas around Nzhelele River Catchment are more informed regarding both Water and Food innovations, technologies and practices. This was because the Nzhelele Area is drier than the Luvuvhu Area; thus, residents must find different ways to save water to have enough for both domestic and agricultural purposes. Many ways to conserve water were found to be applied in this area than in the Luvuvhu area.

Similarities were found in both study sites, although non-renewable energy innovations, technologies, and practices were used more than renewable energy. Solar is the emerging type of renewable energy that is starting to be widely used, although the initial costs were found to be limiting most residences.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The study assessed sustainable WEF nexus smart innovations, technologies and practices in Luvuvhu and Nzhelele River catchments areas, Vhembe District Municipality, Limpopo province, South Africa. A questionnaire survey was used to collect data from 6 different villages, and the data obtained from questionnaires was analysed using IBM SPSS statistical analysis version 29, which helped to generate frequencies from the responses. ArcGIS Inverse distance weighting (IDW) spatial interpolation method. The specific conclusions drawn from the findings are organized thematically below.

6.1.1 Conclusions on Water Innovations and Practices

The findings reveal that water management practices in the study area are highly localized and fragmented. While there is evidence of innovation adoption, it appears to be driven by immediate necessity rather than strategic, integrated planning. Key conclusions for the water sector are that Communities depend on a combination of sources, primarily groundwater and, to a lesser extent, rainwater harvesting. The high dependency on groundwater, particularly in villages such as Tshakhuma and Siloam, raises significant concerns about the long-term sustainability of aquifers in the absence of managed abstraction and recharge strategies.

The adoption of water-efficient technologies like drip irrigation is spatially inconsistent, concentrated in specific villages while absent in others. This suggests that access to technology, capital, and agricultural extension services is unevenly distributed, creating disparities in climate resilience and agricultural potential. The low uptake of rainwater harvesting in several villages, despite its availability, points to a knowledge and resource gap that prevents communities from capitalizing on a valuable, decentralized water source.

6.1.2 Conclusions on Energy Innovations and Practices

The energy landscape is characterized by a dual system of energy poverty and insecurity, presenting a major barrier to sustainable development. The primary conclusions are that the majority of households operate within an energy system that rely on unreliable grid electricity (where available) alongside a heavy dependency on firewood. This reliance on biomass has significant negative consequences for both human and environmental health. The adoption of modern renewable energy innovations, such as solar systems and biogas, is exceptionally low. The study concludes that this is not due to a lack of information but is overwhelmingly a result of high initial costs, which are prohibitive for most low-income households. A lack of access to affordable and reliable energy directly constrains development in other sectors, limiting the use of electric pumps for water, mechanised agricultural processing, and cold storage for preserving food.

6.1.3 Conclusions on Food and Agricultural Innovations

The agricultural system, while central to local livelihoods, is predominantly subsistence-oriented and constrained by significant structural barriers. Key conclusions include that most significant finding is the lack of formal market integration, with the majority of farmers reporting no consistent marketing channels for their produce. This acts as a powerful disincentive for adopting innovations aimed at increasing productivity, as farmers have no reliable way to sell surplus yields.

While effective practices like Conservation Agriculture (CA) are present, their adoption, along with that of other innovations like Sustainable Intensification, is patchy. This points to weaknesses in the agricultural knowledge and innovation system, where information and support are not reaching all farmers equally. The methods used for food processing, preservation, and storage are largely traditional (e.g., sun drying, storage in sacs). The limited use of modern processing and cold storage, often linked to energy deficits, restricts opportunities for value addition and leads to potential post-harvest losses.

The conclusions from the findings of the study also showed that there should be a promotion of the WEF nexus at the local level to provide pathways towards sustainability and desired policy outcomes in rural areas. It was also concluded that hydrological aspects are the mission dimension that should be incorporated into the WEF nexus. In addition, the results showed that socio-economic factors play a critical role in adopting WEF nexus smart innovation, technologies and practices. Managing these sources requires a holistic approach that considers hydrological impacts on the interconnected systems and addresses challenges through sustainable water management, efficient energy use, and resilient agricultural practices. Adaptation and mitigation strategies are essential to ensure the continued availability of these critical resources.

The achievement of a greater impact can be realized through the following strategies:

- Scaling out: This involves expanding the reach of interventions by replicating and disseminating successful approaches, thereby increasing the number of individuals or communities impacted.
- Aligning institutions, policies, and regulations: This is particularly important for addressing cultural and economic barriers, as well as cognitive factors that often hinder the scaling up of promising Indigenous Knowledge (IK), smart practices, and innovations. The integration of IK could play a crucial role in this process.
- Holistic consideration of informational, procedural, and organizational instruments: A comprehensive approach is required to address the interactions and effects of these instruments in advancing WEF innovation and transformation agendas.
- Indigenous Practices (IPs): These could serve as cost-effective vehicles for addressing synergies, fragmentation, and the validation of Indigenous Knowledge (IK). The potential of IPs could be evaluated through multistakeholder WEF-IP platforms that facilitate policy experimentation and social learning.

6.2 Recommendations and Pathways Forward

Based on the interconnected findings of this study, fostering sustainable rural development requires an integrated and holistic approach. The following recommendations provide a strategic pathway forward, structured to reflect a logical progression from immediate foundational actions to long-term systemic change, while identifying the key stakeholders responsible for implementation.

In the immediate short-term, efforts must concentrate on building awareness and leveraging existing local successes. This initial phase requires community leaders and agricultural extension services to spearhead practical awareness campaigns and workshops, focusing on tangible themes such as saving water and saving electricity costs rather than abstract concepts. A crucial action is to identify the farmers who are already successfully using innovations like drip irrigation or rainwater harvesting, so their methods can be documented and shared through peer-to-peer learning. Simultaneously, researchers should work to systematically document and validate local Indigenous Knowledge related to resource management and disseminate this study's findings in accessible formats, such as policy briefs and community pamphlets, to ensure the knowledge generated is put to immediate practical use.

Building on this foundation, the medium-term timeframe should shift towards piloting interventions and strengthening local institutions. During this phase, local government and partner NGOs should design and implement pilot projects to replicate successful innovations in the identified coldspot villages, for instance by establishing demonstration plots or facilitating the formation of farmer cooperatives to improve collective marketing power. Concurrently, it is critical for provincial and national policymakers to design and test targeted financial instruments, such as micro-loans, subsidies, or rent-to-own schemes, to address the prohibitive upfront cost of renewable energy and water-saving technologies. This period should also see the establishment of multi-stakeholder platforms where community members, researchers, and officials can co-design blended innovations that integrate the resilience of Indigenous Knowledge with the efficiency of modern science.

Long-term actions must focus on embedding these successful approaches into systemic and institutional frameworks for lasting impact. At this stage, national and provincial policymakers should scale up the most effective financial models into official programs, making clean energy and water technologies broadly affordable. This must be supported by significant investment in rural infrastructure, such as farm-to-market roads and storage facilities, and a dedicated effort to harmonize the policies of the departments of agriculture, energy, and water to eliminate conflicts and support integrated management. A key objective for local government will be to formally embed WEF nexus principles into the official Integrated Development Plan (IDP) cycle. For their part, researchers should transition to conducting longitudinal studies to monitor the long-term socio-economic and environmental impacts of these interventions, ensuring that the pathway to sustainable development is both effective and adaptive. Table 6.1 categorizes these recommendations by type (Policy, Practice, Research), assigned a feasible timeframe, and directed at the primary stakeholders responsible for action.

Table 10.1: Recommendations and Actionable Pathways for the WEF Nexus

Timeframe	**Recommendation Type**	**Specific Recommendation / Action**	**Primary Target Audience(s)**
Short-Term (0–18 Months)	Practice / Capacity Building	Initiate practical, local-language WEF nexus awareness campaigns and workshops focusing on tangible benefits (e.g., cost savings).	Community Leaders, Agricultural Extension Services, Local NGOs
	Practice	Identify and document the methods of successful "champion farmers" to create a local knowledge base for peer-to-peer learning.	Agricultural Extension Services, Researchers
	Practice	Establish accessible market information systems (e.g., using WhatsApp) for farmers to share information on local prices and demand.	Community Leaders, Farmer Groups, Extension Services
	Research	Systematically document and validate existing Indigenous Knowledge (IK) related to water conservation, food preservation, and soil management.	Researchers, Academic Institutions
	Research / Outreach	Disseminate key study findings in accessible formats (policy briefs, pamphlets, community presentations) to ensure immediate uptake.	Researchers, Extension Services

Table 11continue……….

Medium-Term (1.5–3 Years)	Practice / Implementation	Design and implement pilot projects to "scale out" successful innovations (e.g., drip irrigation, rainwater tanks) in identified "coldspot" villages.	Local Government (Municipalities), NGOs, Extension Services
	Practice / Institutional	Facilitate the formation and strengthening of farmer cooperatives to enable collective marketing, bulk purchasing, and better access to credit.	Department of Agriculture, Extension Services, Community Leaders
	Policy / Financial	Design and pilot targeted financial instruments (e.g., micro-loans, rent-to-own schemes, subsidies) to address the high upfront cost of renewable energy and water-saving technologies.	Provincial/National Policymakers, Development Banks, Financial Institutions
	Research / Practice	Establish multi-stakeholder platforms to co-design and test "blended" innovations that integrate Indigenous Knowledge with modern technologies.	Researchers, Community Leaders, NGOs, Extension Services
Long-Term (3+ Years)	Policy / Governance	Scale up successful pilot financial models into official provincial or national programs to ensure widespread affordability of clean energy and water technologies.	National/Provincial Government, Treasury, Development Banks
	Policy / Infrastructure	Invest in critical rural infrastructure (e.g., farm-to-market roads, community storage facilities) and create supportive regulations to ease smallholder access to formal markets.	National/Provincial Government (Public Works, Agriculture), District Municipalities
	Policy / Institutional	Formally integrate WEF nexus principles and trade-off analysis into the official Integrated Development Plan (IDP) cycle for municipalities.	Department of Cooperative Governance and Traditional Affairs (COGTA), Municipal Planners
	Policy / Governance	Harmonize departmental policies across Water, Energy, Agriculture, and Environment to eliminate conflicting objectives and support integrated resource management at the local level.	National Government Ministries and Departments
	Research	Conduct longitudinal studies to monitor and evaluate the long-term socio-economic and environmental impacts of the implemented WEF nexus interventions.	Researchers, Academic Institutions, Funding Bodies (e.g., WRC)

There is a need to improve and enhance WEF frameworks to be more applicable to South African rural areas at the household level. Innovations such as improved infrastructure, WEF supply, enhanced models and technological advances should be considered when dealing with WEF nexus in rural areas. Thus, maintaining resource security for future use while improving rural livelihoods through integrated resource distribution, planning, and management, as well as enhancing a better understanding of the nexus approach whilst maximising the positive synergies and identifying how best to build resilience into rural livelihoods and wellbeing.

More innovative technologies should be brought to rural parts of the world, as some villages have the resources but lack infrastructure; hence, innovative technologies such as power stations with lower emissions, dry-cooled power plants, smart irrigation technologies, renewable energy technologies such as biofuels, wind, and the use of abundant solar energy are relevant innovations for sustaining rural resources.

This study recommends that there be additional studies wherein the WEF nexus will be integrated with sustainability and Indigenous Knowledge Systems (IKS) as this can provide a more holistic approach to addressing the challenges faced by rural communities. Indigenous knowledge often offers time-tested, context-specific solutions that are sustainable and aligned with local ecosystems. By incorporating Indigenous knowledge into the WEF nexus, future studies can explore how traditional practices in water management, agriculture, and energy use contribute to sustainable development. This integration could lead to more culturally and socially sensitive and effective interventions that empower rural communities, preserving their heritage while enhancing resilience and sustainability.

Additionally, the study identified indicators that highlight that rural areas are very dependent on food production, which requires a huge quantity of water and energy; therefore, there is a need to improve the understanding of how the WEF nexus can support food production and supply, including strengthening the capacity of smallholder farmers to enhance productivity yields, thus reducing poverty.

The study indicates a need for thorough investigations into the potential impacts of future hydrology-related changes, climate effects, land use, agriculture, and energy consumption within the context of the Water-Energy-Food (WEF) nexus. Related research studies should include hydrological components such as water quality and climate change as it was significant to humans' health and well-being and environmental health that are not often clearly covered within the nexus concept. Furthermore, the current study also recommends conducting additional research that utilises the district or local development model. This approach is suggested to improve community engagement and ensure inclusive actions to sustain the elements and interconnected resources of the Water-Energy-Food (WEF) nexus in rural areas.

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APPENDICES

APPENDIX A1: QUESTIONNAIRE FOR INDIVIDUALS / HOUSELHOLDS

50 Years WATER RESEARCH COMMISSION

PROJECT WRC C2020/2021-00392

Project Title:

Assessing sustainable water, energy and food (WEF) nexus smart innovations, technologies and practices in Luvuvhu and Nzhelele River catchments areas, Vhembe District Municipality, Limpopo province, South Africa.

APPENDIX A: QUESTIONNAIRE FOR INDIVIDUALS / HOUSELHOLDS

CLOVITA CONSULTING SERVICES

Ozone AGRI DEVELOPMENT SOLUTIONS

Table of Contents

BACKGROUND

This document presents the research data collection tools for Water Research Commission (WRC) funded project titled "Integrating water-energy-food (WEF) nexus innovations and practices into policy, governance and institutional frameworks for sustainable development in Vhembe District Municipality, Limpopo Province, South Africa". Motar and Daher (2016)[1] posit that WEF nexus research should include local level stakeholders. Therefore, this research seeks support the decision-making process of the nexus assessment by collecting new knowledge which is context specific (Melloni et al., 2020[2]) to local setting.

ETHICAL CONSIDERATIONS

The project will respect at its core the five ethical principles that researchers need to adhere to:

a) obtain informed consent from potential research participants;
b) minimize the risk of harm to participants;
c) protect the participants' anonymity and confidentiality;
d) avoid using deceptive practices; and
e) give participants the right to withdraw from the research.

In addition to the five "gold" standard principles, integrity and transparency shall be vital in our research.

INFORMED CONSENT

The human subjects in any research project must participate willingly, having been adequately informed about the research. Informed consent in our study will entail a process of telling potential research participants about the key elements of the research study and what their participation will involve. The consent process will also include providing a written consent document containing the required information (See Annex A) for the proposed Consent Form) and the presentation of that information to prospective participants to concur.

INTELLECTUAL PROPERTY (IP) CONSIDERATIONS

With regard to intellectual property (IP), data collected, data collection tool and reports of this study shall be an intellectual property of the WRC. This will be guided by the Intellectual Property Rights from Publicly Financed Research and Development Act 51 of 2008 (IP Act) (Republic of South Africa, 2008).

[1] Rabi H. Mohtar & Bassel Daher (2016) Water-Energy-Food Nexus Framework for facilitating multi-stakeholder dialogue, Water International, 41:5, 655-661, DOI: 10.1080/02508060.2016.1149759
[2] Melloni et al., 2020. A Stakeholder Analysis for a Water-Energy-Food Nexus Evaluation in an Atlantic Forest Area: Implications for an Integrated Assessment and a Participatory Approach.

SECTION 1: INTERVIEW DETAILS

This Section is designed to gather information about the study respondents (and/or participants). Respondents are those persons who will be invited to participate in this research study and have actually taken part in the study.

Numbering	Required to fill-in/Question	Instruction		
1.1	Supervisor's Name	Indicate the name of the supervisor		
1.2	Enumerator's Name	Indicate name of the supervisor		
1.3	Supervisor's Check Date	yyyy-mm-dd To be completed by supervisor		
1.4	Name of the Respondent	Name and Surname		
1.5	Respondent's Household (HH) Status	Choose from:		
		- Household Head		
		- Spouse		
		- Child		
		- Relative		
1.6	Gender of the Head of the Respondent	Choose from:		
		- Male		
		- Female		
		- Prefer not to say		
1.7	Age category of the Respondent	Choose from:		
		- 20 and under		
		- 21-30		
		- 31-40		
		- 41-50		
		- 51-60		
		- Above 60		
1.8	Highest Education Level of the Respondent	Choose from:		
		- No schooling		
		- Primary Education		
		- Secondary Education		
		- TVET/College Education		
		- University Education		
1.9	Employment Status of the Respondent	Ask if the respondent is employed:		
		Employment status	Yes	No
		- Formal (public servant, teacher, others....)		
		- Informal employment (not salarised)		
		- Retired		
		- Umeployed		
		- Self employed		

SECTION 2: DEMOGRAPHIC INFORMATION (HOUSEHOLD TYPOLOGY)

The collected demographic information in this Section will allow the Research Team to better understand certain background characteristics of an audience, whether it's their age, race, ethnicity, income, work situation, marital status, etc.

Numbering	Required to fill-in/Question	Instruction			
2.1	Indicate Village Location	Municipality ward within Vhembe with reference to pilot site			
2.2	Indicate Village Name	Village with reference to pilot siteVillage of respondent			
	How many members live in this household including you?				
2.3	Household Physical Assets: What are the assets within the household?	Select water related assets			
		Choose by tickingsource from the list (*multiple entries allowed*):			
	➔ Select = ticking from pre-programmed list. Multiple entries are allowed.	- Household Municipal Tap			
		- Communal Municipal Tap			
		- Household Borehole			
		- Communal Borehole			
		- Fountain			
		- River steam			
		- Rainwater			
		- Gravity Scheme			
		-			
2.4		Select agriculture production related assets			
		Crops:		**Livestock:**	
		- HandtoolsSpade(Digging	-	- Local	-
		- fork;Rake,Hand Hoe)		- Chickens	
		- fork;Rake,Hand Hoe)		- Commercial	
		- Ox-drawn farm implements (e.g., plough, cultivator, ridger, cart)	-	- Poultry	
				- Small stock - goats/sheep	-
				- Small stock -	
		- Tractor		- sheep)	
		- Home garden		- Cattle – Beef	
		- Field within HH		- Cattle Dairy	
		- Filed outside HH		- *Other, name:*	
		- Commercial orchard		-	

		- *Other, name:*	
		-	
2.5		**Food storage, processing or preservation (i.e., post-harvest loss management):**	
		- Processing - 1. Hammer milling (locally) - 2. Skimming - 3. Purchases already processed - Pasteurisation - Skimming - Fermentation - 4. Any other, name	
		- **Food preservation** - **Sundrying** - **Freezer/fridge** - **Ash** - **Fumigation(chemicals/pills)** - **Blanching (boiling vegetables for sometime before dying)** - **Cold storage** - **Salting** - **Smoking**	
		- Storage - Mud bin - Congregated steel house - Drums - Spare rooms - Bags - Garage - Others	
2.6		**ICT/Information access and related assets:**	
		- Telephone line	
		- **Newspapers and magazines**	-
		- Cellphone Network Access	
		- TV	
		- Radio	

SECTION 3: A TYPOLOGY OF THE WEF NEXUS

The purpose of this Section is to characterize the Water, Energy and Food (Agriculture) nexus elements. To provide context, in this Section, we will collect data to assist describe concretely what is happening (i.e., the current situation of the WEF elements within the pilot sites). This will then make it easy for the reader to have a better understanding of the background and the results of the research.

Section 3.1: Typology of Household Water Uses

Numbering	Required to fill-in/Question	Instruction	
3.1.1	Indicate the source of household water? ➔ some questions will have sub-questions.	***Name the main source from among the selected***	
		• Household Municipal Tap	
		• Communal Municipal Tap	
		• Household Borehole	
		• Communal Borehole	
		• Fountain	
		• River steam	
		• Rainwater	
		• Gravity Scheme	
		Other, name:	
3.1.2	Indicate main water treatment method.	Choose from:	
		• Household boiling	
		• Household chlorine treatment	
		• Central chlorine treatment	
		• Jik	
		• Filtering	
		• *Other, name:*	
3.1.3	Indicate location/distance to main water source.	Choose from:	
		• Within the HH	
		• Within 1 KM of the HH	
		• Beyond 1 KM of the HH	
3.1.4	List the uses of water by the household	**Choose by ticking source from the list (*multiple entries allowed*):**	

		• HH consumption and use(cooking, drinking, laundry)	
		• Vegetable husbandry(irrigation)	
		• Livestock husbandry (watering)	
		• Other commercial activity, name:	
		Indicate the main use of water by the household……………………………………………….	
3.1.5	How often do you receive water?	Consistency of water supply happening:	
		- Daily	
		- Twice or less a week	
		- Less than 3 times a month	
		- Never	
		- Unreliable to never	
		- More than 2 times a week	
		- Other (please specify)	

Section 3.2: Typology of Household Energy Uses

Numbering	Required to fill-in/Question	Instruction	
3.2.1	Indicate the type of household energy used (at HH level and/or field outside the HH)	Choose by ticking from the list (*multiple entry allowed*)	
		• Biomass (Fuelwood, animal dung, biogas etc.)	
		• Eskom/Municipality electricity	
		• Paraffin	
		• Liquid petroleum gas (LPG)	
		• Renewable energy technologies (solar panels, solar water heaters etc.)	
		• Coal	
		• Other (specify)	
		Name the main source among the selected ………………………………………………………………………	
3.2.2	Indicate the main uses of energy.	**Choose by ticking source from the list (*multiple entries allowed*):**	
		• Heating (water, pottery, space)	

		• Lighting	
		• Cooking	
		• Cooling	
		• Refrigeration	
		• Television	
		• Charging computers and other devices such as cellphones	
		- **Name the main use of the source selected** above………………………………………………………………………	

Section 3.3: Typology of Household Agriculture Farming Systems

Numbering	Required to fill-in/Question	Instruction	
3.3.1	Crop Farming System	**Total land planted** _________________	
		Crop Production System	
		1. Irrigated	
		2. Dryland	
		3. Both	
		Where	
		1. Within Homestead	
		2. Outside Homestead	
		3. Both	
		Commercialisation Level	
		1. Subsistince(Home use)	
		2. Commercial(Market oriented	
		3. Both	
		Market channels:	
		1. Farmgate(Homestead)	
		2. Vendors	
		3. Official channel (i.e. Spar)	
		4. None	
	Irrigation type used	1. Drip	
		2. Bucket (hose pipe)	

		3. Furrow	
		4. Sprinkler	
		5. Any other, name	
	Challenges on type of irrigation	1. Increases erosion	
		2. Uses a lot of water	
		3. Labour intensive	
		4. Any other, name	
3.3.2	Indicate for fruit farming by marking against appropriate kind Horticulture Farming System	**Total land planted** ________________	
		Type:	
		1.Backyard	
		2. Orchard	
		3. Both	
		Commercialisation Level	
		1.Subsistence (Home use)	
		2. Commercial (Market Oriented)	
		3. Both	
		Labour:	
		1. own labour	
		2. Hired	
		3 both 0wn and hired	
		Market channels:	
		1. Farmgate(Homestead)	
		2. Vendors	
		3. Official channel (i.e. Spar)	
		4. None	
	The importance of water to the farming system (Low or High)	1. Low	
		2. High	
		3. Don't Know	
	Importance of energy to the farming system (Low or High)	1. Low	
		2. High	
		3. Don't Know	
3.3.3	Livestock Farming System	Indicate for livestock farming:	

		Type:	
		1.Intensive	
		2. Extensive	
		3. Both	
		Commercialisation Level	
		1.Subsistence (Home use)	
		2. Commercial (Market Oriented)	
		3. Both	
		Labour:	
		1. own labour	
		2. Hired	
		3 both 0wn and hired	
		Market channels:	
		1. Farmgate(Homestead)	
		2. Vendors	
		3. Official channel (i.e. Spar)	
		4. None	
	The importance of water to the farming system (Low or High)	Low	
		High	
		Don't Know	
	Importance of energy to the farming system (Low or High)	Low	
		High	
		Don't Know	

Section 3.4: Typology of Food Security and Food Sufficiency

Numbering	Required to fill-in/Question	Response			
	Food Security	**Instructions:** *Please for each statement/question whether the statement/question was often, sometimes, or never in the last 12 months(* ***mark only one option across arow)***			
3.4.1	"I worry whether our food would run-out."	*never*	*sometimes*	*often*	
3.4.2	"The food that we produced just didn't last, and we didn't have money to get more."	*never*	*sometimes*	*often*	
3.4.3	"We couldn't afford to eat balanced meals."	*never*	*sometimes*	*often*	
3.4.4	"We couldn't feed the children a balanced meal because we couldn't afford that."	*never*	*sometimes*	*often*	
3.4.5	In the last 12 months, did you ever eat less than you felt you should because there wasn't enough food?	*never*	*sometimes*	*often*	
3.4.6	In the last 12 months, were you ever hungry but didn't eat because there wasn't enough food?	*never*	*sometimes*	*often*	
3.4.7	In the last 12 months, did you or other adults in your household ever not eat for a whole day because there wasn't Enough money for food?	*never*	*sometimes*	*often*	
3.4.8	In the last 12 months, did you ever cut the size of any of the children's meals because there wasn't enough food?	*never*	*sometimes*	*often*	
	Food Sufficiency				
3.4.9	Which of these statements best describes the food eaten in your household in the last 12 months *Instructions: Please read the statements and ask the respondent to select his/her best choice(* ***Only one choice)***	We always have enough to eat and the kinds of food we want;	We have enough to eat but not always the kinds of food we want;	Sometimes we don't have enough to eat; or	Often we don't have enough to eat?

3.4.10	Here are some reasons why people don't always have enough to eat. For each one, please tell me if that is a reason why You don't always have enough to eat.	**Choose by ticking source from the list (*multiple entries allowed*):** *(please specfy by ticking on the left)*	
		Agriculture low production	
		Agriculture post-harvest loss	
		Not enough money/income for food	
		Lack of water	
		No access to cooking energy source	
		Too hard to get to the store	
		Drought	
		Theft	
		Not able to cook or eat because of health problems;	
		Other *(please specfy)*	

SECTION 4: WEF TECHNOLOGICAL INNOVATIONS AND PRACTICES

In the specified field: 1) Indicate the WEF technological innovations and practices you are currently using; 2) indicate how you are using them, 3) mention the related benefits, and 4) mention the related challenges.

The purpose this Section is to understand each WEF components and relationships among the component parts found within the WEF system. This will help explain, better understand, and explore research subjects' opinions, behavior, experiences, phenomenon, etc.

Section 4.1: Water Technological Innovations and Practices

Numbering	**Water technological Innovation and Practices** **Choose from the list as dictated by the respondent**		**Details about the utilized technological Innovation and Practices** **(Required to fill-in/Question)**			**Prioritization**[3]
	Indicate the sub-category as per WEF nexus	**Utilized technological Innovation and Practices** **(Indicate Yes or No)**	**Indicate how you are using the Water technological Innovation and Practice**	**Give us the reasons why you are using the technological Innovation and Practice**	**Give us the challenges you are experiencing using the technological Innovation and Practice**	**Rank the perceived benefit of the technological Innovation and Practice** **(Scale of 1 to5)**
4.1.1	Rainwater	Water harvesting using large dams	**1.Irrigation** **2. HH consumption(cooking and drinking)** **3. sanitation only** **4. Irrigation**	**1.**		
		Water harvesting using small dams (i.e., for agriculture)	**1.Irrigation** **2. HH consumption (cooking and drinking)**			

[3] The Likert scale used to prioritize the WEF identifies technological Innovation and Practice is: *1 = Extremely poor, 2 = Very poor, 3 = neutral, 4 = good, 5 = excellent*

Numbering	Water technological Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[3]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using the Water technological Innovation and Practice	Give us the reasons why you are using the technological Innovation and Practice	Give us the challenges you are experiencing using the technological Innovation and Practice	Rank the perceived benefit of the technological Innovation and Practice (Scale of 1 to5)
			3. sanitation only **4. Irrigation**			
		Household storage (e.g., jojo tanks).	**1.Irrigation** **2. HH consumption (cooking and drinking)** **3. sanitation only** **4. Irrigation**			
4.1.2	Groundwater	Water detection technologies (i.e., Allen technology)	**1.Irrigation** **2. HH consumption (cooking and drinking)** **3. sanitation only** **4. Irrigation**			
		Water drawing using Wind/Solar powered boreholes or hand pumped				
		Artificial Groundwater recharge into confined aquifers for future use				

Numbering	Water technological Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[3]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using the Water technological Innovation and Practice	Give us the reasons why you are using the technological Innovation and Practice	Give us the challenges you are experiencing using the technological Innovation and Practice	Rank the perceived benefit of the technological Innovation and Practice (Scale of 1 to5)
4.1.3	Water Recycling	Wastewater treatment with Effective Microorganisms (EM) (i.e., Photosynthetic bacteria, Lactic acid bacteria, Yeast)				
		Grey water reuse				
4.1.4	River streams	Digital water monitoring using satellite images (i.e.,to track in- and out-flows).				
4.1.5	Reducing water loss	Maintenance of bulk water storage and distribution networks (e.g., infrastructure routine maintenance and use call centers to log/report leaks for timely repairs) Promoting use of water saving devices in institutions and households (e.g. washing machines, showers, toilet systems)				

Numbering	Water technological Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[3]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using the Water technological Innovation and Practice	Give us the reasons why you are using the technological Innovation and Practice	Give us the challenges you are experiencing using the technological Innovation and Practice	Rank the perceived benefit of the technological Innovation and Practice (Scale of 1 to5)
4.1.6	Other indigenous water use related innovations and practices	Ask the respondent to list.				

Section 4.2: Agriculture and Food Technological Innovations and Practices

Numbering	Food and Agriculture Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[4]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using the Water/Food technological Innovation and Practice	Give us the reasons why you are using the technological Innovation and Practice	Give us the challenges you are experiencing using the technological Innovation and Practice	Rank the perceived benefit of the technological Innovation and Practice (Scale of 1 to5)
4.2.1	Conservation agriculture	- Zero cultivation				
		- Raised Bed				
		- Double dug bed				
		- Agroforestry				
		- Mulching				
		- Organic (Livestock /plant manure)				
		- IPM (integrated pest management)				
		- Others				
		-	Chose from here;	Choose from here: 1. Drought 2. Premium price 3. High cost of commercial input 4. Concern for environment 5. Any other: name 6. none	Choose from here: 1. lack of knowhow 2. labour intensive 3. pest problem 4. cost 5. Any other, name	
4.2.2	Smart irrigation (technologies that reduce water used, reduce pollution, i.e use of solar to pump)	- Drip irrigation				
		- Handheld devices to measure soil moisture (chameleon technology)				
		- Greenhouses/ screenhouses				
		-		Choose from: 1. Increase productivity 2. Affiliated to a marketer who encourages its use. 3. Reduced cost 4. Use less water 5. Any other, name	Choose from: 1. Lack of awareness 2. High initial cost 3. Lack capital Blockage nozzles 4. Lack of knowhow	
4.2.3	Sustainable intensification	- Use of tunnels (screen houses/green houses)				
		- Organic farming				
		- Crop rotation				
		- Agroforestry				
		- Use of hydroponics				
		- Fallowing				
		- Integrated organic and inorganic				
4.2.4	Use of disaster related insurance	Index-based insurance (for floods)				
4.2.5	Other indigenous agriculture related innovations and practices	Ask the respondent to list.				

[4] 4 The Likert scale used to prioritize the WEF identifies technological Innovation and Practice is: *1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = excellent*

Section 4.3: Energy Innovations and Practices

Numbering	Energy Innovation and Practices Choose from the list as dictated by the respondent		Details about the utilized technological Innovation and Practices (Required to fill-in/Question)			Prioritization[5]
	Indicate the sub-category as per WEF nexus	Utilized technological Innovation and Practices (Indicate Yes or No)	Indicate how you are using the Innovation and Practice	Give us the reasons why you are using the technological Innovation and Practices	Give us the challenges you are experiencing using the technological Innovation and Practice	Rank the perceived benefit of the Water technological Innovation and Practices (Scale of 1 to 5)
4.3.1	Non-Renewable	- Coal				
		- Electricity				
		- Firewood				
		- Paraffin				
		- LPG / Gas				
4.3.2	Renewable	- Biogas digester				
		- Solar (PV or Solar water heaters)				
		- Wind				
4.3.3	Other indigenous energy related innovations and practices	Ask the respondent to list.				

[5] [5] The Likert scale used to prioritize the WEF identifies technological Innovation and Practice is: *1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = excellent*

SECTION 5: ACCESS TO AND USE OF WEF RESOURCES

Section 5.1: WEF resource use

Numbering	WEF Resource	Type and source	Main use for which resource is used (mark against as many uses for each as possible)
5.1.1	Food/Agriculture	Fruit trees	Consumption: windbreak; Sale; Landscaping; Cultural heritage
		Fodder	Livestock; sale
		Vegetables	Sale, consumption, both sale and consumption
		Cereals and pulses e.g.	Sale, consumption; both sale and consumption
		Livestock	Sale, consumption; both sale and consumption
5.1.2	Energy	Solar	Lighting, Tv, radio, charging
		Mains Electricity	Lighting, cooking, heating; cooling
		Wind	Lighting, cooking, heating; cooling
		Biomass (Fuelwood, animal dung, biogas etc.)	Cooking; Heating; Sale
5.2.3	Water	Borehole	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock
		River	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock
		Rainwater Harvesting	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock
		Dam	Drinking; Cooking; Irrigation; sanitation only; Irrigation; Livestock; Car Wash

Section 5.2: WEF resource access and use rights

Numbering	WEF Resource	Dimension	Is any of the dimension in the previous column an issue of concern Yes / NO	If Yes state, the issue (e.g. Permits, metering, rules, rationing for each of the dimensions)	Further comment if any
5.2.1	Water	Domestic use			

		Agricultural use/ irrigation			
		Irrigation times			
5.2.2	Energy	Regulation on type to use			
		Reliability of supply			
		Cost of alternatives			
		Access to alternatives			
5.2.3	Food Production	Land for crop production			
5.2.4	Land	Zoning restrictions			

Section 5.3: Land Resource Use for Agriculture

Numbering	**Land Resource**	**Instruction**
5.3.1	Land/ food production	Indicate total land size (in hectors)
		Indicate size of land planted in the current or last planning season (in hectors)

SECTION 6: GOVERNANCE, INSTITUTIONS AND POLICY DIMENSIONS

Section 6.1: Names of local institutions

What institutions are there which affect or influence your use and management of water, energy, and food production in your household/community?

Numbering	**WEF sector**	**Institutions(Name or list as many)**
6.1.1	Water	
	Energy	
	Food production	

Section 6.2: Membership in local institutions

Are you a member in any of the following?

Numbering	**Institution Type**	**Yes**	**No**
6.2.1	Water Users Association		
	Savings and credit society		
	Micro credit finance		
	Any other Interest Group (Name it)		

SECTION 7: FINANCIAL SUPPORT, EXTENSION AND ADOPTION

Section 7.1: WEF financing

Have you received any financing towards any of the following?

Numbering	WEF	Credit source	Yes/No		Specific Purpose on which credit was utilised	Any comment
7.1.1	Water development	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		
7.1.2	Energy development	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		
7.1.3	Food production	Cooperative	Yes	No		
		Bank	Yes	No		
		Microcredit	Yes	No		
		Family	Yes	No		
		Local saving group	Yes	No		
		Grant (specify)	Yes	No		

Section 7.2: Communication channels and extension services on WEF technologies

For each of the information sources provide the frequency you have had in the last one year

Numbering	Source of information for each WEF	Source of information	Yes/ No		How frequent do you receive the information (for each source)					
7.2.1	Energy smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually

7.2.2	Water Smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Autonomous (own effort)	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
7.2.3	Land use for food production smart technologies	Public extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Private extension	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Radio / TV	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Newspaper	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Online	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Peers	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Scientific publication	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Autonomous (own effort)	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually
		Innovation platforms	Yes	No	Daily	Weekly	Monthly	Quarterly	Biannually	Annually

Section 7.3: Players in WEF technology promotion and adoption

Numbering	Smart technology	Specific WEF smart innovation	Who promotes	Constraints	Rank the constraints named (Use 1 for the most pressing)
7.3.1	Energy	Solar Energy saving Wind Any Other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort) Innovation platforms	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	
7.3.2	Water use	Water recycling Water harvesting/ roof harvesting Drip irrigation Hydroponics Any other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort) Innovations platforms	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	
7.3.3	Land use	Manuring Cover crops Mulching Zero tillage Climate manipulation /Green houses	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives	

		Runoff capture Any other	International organisation Autonomous (own effort) Innovation platforms	Lack Access to alternatives Any other	

Section 7.4: Factors influencing adoption of smart WEF technologies

What has influenced or likely to influence you adopt smart technologies?

Numbering	WEF Technology	Factor	List not more than 5 in order of importance (1 most important)
7.4.1	Energy smart technologies	Knowledge/ education	
		Finance	
		Care for environment	
		Social network	
		Peers	
		Family spillovers	
		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	
7.4.2	Water smart Technologies	Knowledge/ education	
		Finance	
		Value for environment	
		Social network	
		Peers	
		Family spillovers	
		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	
7.4.3	Land use/ food production smart technologies	Knowledge/ education	
		Finance	
		Value for environment	
		Social network	
		Peers	
		Family spillovers	
		Market access	
		Grant	
		High returns	
		Cost saving	
		Reliability	

Section 7.5: Barriers to WEF smart technologies

Numbering	WEF resource	Barrier	Yes / No		Rank the barriers (Use 1 as the most pressing)
7.5.1	Energy smart technologies	Initial cost	yes	no	
		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	
		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	

7.5.2	Water Smart technology	Initial cost	yes	no	
		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	
		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	
7.5.3	Land use smart technologies	Initial cost	yes	no	
		Technical Knowhow	yes	no	
		Government regulation and policies	yes	no	
		Lack of information	yes	no	
		Lack of capital/ credit	yes	no	
		Lack of alternatives	yes	no	
		High cost of alternatives	yes	no	
		Any other	yes	no	

To ensure that the proposed mixed model approach is robust enough, Sections 8 interview questions are open-ended questions so that in-depth information will be collected.

SECTION 8: SUGGESTIONS ON WEF NEXUS SOLUTIONS

Numbering	**Required to fill-in/Question**	**Instruction** *Please read the statements and ask the respondent to answer to their best ability.*
8.1	What are the main challenges n yiur household with respect to 1. Water availability? 2. Cost of water 3. Consistency in supply	
8.2	What should be done to eradicate water insecurity?	
8.3	What is the main challenges n you household with respect to Energy availability? 1. Energy availability? 2. Cost of Energy 3. Consistency in supply	
8.4	What should be done to eradicate energy scarcity (if any)?	

8.5	What are the main challenges n yiur household with respect to Food availability? 1. Food availability? 2. Cost of food 3. Access to food	
8.6	What should be done to eradicate food insecurity?	

SECTION 9: Family income

	Farm	Formal Employment	Informal Employment
Householsd Head			
Remittances from relatives			
1. 0-2000			
2. 2001-4000			
3. 4001-6000			
4. 6001- 8000			
5. 8001-10,000			
6. Above 10000			
		(can just indicate the job type)	

APPENDIX A2: QUESTIONNAIRE FOR GROUPS AND INSTITUTIONS

PROJECT WRC C2020/2021-00392

Project Title:

Integrating water-energy-food nexus innovations and practices into policy, governance and institutional frameworks for sustainable development in Vhembe District, Limpopo Province, South Africa

APPENDIX C2: QUESTIONNAIRE FOR GROUPS AND INSTITUTIONS

CLOVITA CONSULTING SERVICES

Table of Contents

BACKGROUND

This document presents the research data collection tools for Water Research Commission (WRC) funded project titled "Integrating water-energy-food (WEF) nexus innovations and practices into policy, governance and institutional frameworks for sustainable development in Vhembe District Municipality, Limpopo Province, South Africa". Motar and Daher (2016)[1] posit that WEF nexus research should include local level stakeholders. Therefore, this research seeks support the decision-making process of the nexus assessment by collecting new knowledge which is context specific (Melloni et al., 2020[2]) to local setting.

ETHICAL CONSIDERATIONS

The project will respect at its core the five ethical principles that researchers need to adhere to:

a) obtain informed consent from potential research participants;
b) minimize the risk of harm to participants;
c) protect the participants' anonymity and confidentiality;
d) avoid using deceptive practices; and
e) give participants the right to withdraw from the research.

In addition to the five "gold" standard principles, integrity and transparency shall be vital in our research.

INFORMED CONSENT

The human subjects in any research project must participate willingly, having been adequately informed about the research. Informed consent in our study will entail a process of telling potential research participants about the key elements of the research study and what their participation will involve. The consent process will also include providing a written consent document containing the required information (See Annex A) for the proposed Consent Form) and the presentation of that information to prospective participants to concur.

INTELLECTUAL PROPERTY (IP) CONSIDERATIONS

With regard to intellectual property (IP), data collected, data collection tool and reports of this study shall be an intellectual property of the WRC. This will be guided by the Intellectual Property Rights from Publicly Financed Research and Development Act 51 of 2008 (IP Act) (Republic of South Africa, 2008).

SECTION 1: GROUP OR INSTITUTION DETAILS

1. Actor name and mandate

Sector	Actor	Mandate	Instruments and tools on access and use of WEF resources
Energy			Permits Tariffs Education/ informational
Water			
Land and land use			

2. Do you have coordination mechanism with other sectors (named in 1) at local and national levels?
3. Are there community engagement plans in your area regarding water use/ energy/ land use
4. What are some of the resource conflicts and grievance redress mechanisms about access, use and control of the WEF resources in your area and how do you resolve them?
5. How is Environmental, social and climate impact assessment integrated into the planning processes of your area
6. How are financing intermediaries integrated into the planning processes of your area?
7. What incentives do you have regarding scaling of climate smart technologies?
8. Do you have partnership with regard to research, implementation and steering of your mandate?
9. What are your intervention and strategies regarding the following?

Sector and actor	Access (poverty and equity)	Sustainability (economic, social, and environmental	Efficiency	Climate change vulnerability (adaptation and mitigation and resilience building)
Water – Water smart energy systems 1. 2. 3.				
Energy – Energy smart water systems 1.				

2. 3.				
Land use=- Water land smart food systems 1. 2. 3.				

SECTION 2: GOVERNANCE SYSTEMS

Section 2.1: Governance actors and their role in WEF

Numbering	WEF sector	Actor (As many actors as there could be)	Role (Tick against the role for each of the actor)
6.3.1	Water		Regulatory (Licensing/ permits) Advocacy Supplier Financing Training/ Awareness creation Policy Capacity building Advocacy /lobbying Conflict resolution Sustainability and resilience building
6.3.2	Energy		Regulatory (Licensing/ permits) Advocacy Supplier Financing Training/ Awareness creation Policy Capacity building Advocacy /lobbying Conflict resolution Sustainability and resilience building
6.3.3	Food production /Irrigation and land use		Regulatory (Licensing/ permits) Input Supplier Financing Training/ Awareness creation Policy Capacity building Advocacy /lobbying Conflict resolution Sustainability and resilience building

Section 2.2: Institutional, regulations and policy support

2.2.1: Institutions

a) What institutions are there which affect or influence your use and management of water, energy and food production in your household/community? (**Please list)**

Numbering	WEF sector	Institutions
2.2.1.1	Water	
	Energy	
	Food	

b) In your opinion what changes need to be made to improve the roles of the institutions in supporting your effective and sustainable use and management of water, energy and food production in your household/community? (**Please list**)

Numbering	Suggested changes to improve the roles of the institutions WEF Nexus Elements		
	Water	**Energy**	**Food production**
2.2.1.2			

2.2.2: Rules, regulations, and laws

a) What rules, regulations, and laws* are there which affect or influence your use and management of water, energy and food production in your household/community? (**Please list)**

Numbering	WEF sector	Rules	laws	Regulations
2.2.2.1	Water	1. 2. 3.		
2.2.2.2	Energy	1. 2. 3.		
2.2.2.3	Food	1. 2. 3.		

b) **In your opinion what changes need to be made to improve the roles of the rules, regulations, and laws in supporting your effective and sustainable use and management of water, energy and food production in your household/community? (Please list)**

Numbering	Changes need to be made to improve the roles of the rules, regulations, and laws in supporting WEF nexus elements		
	Water	Energy	Food production
2.2.2.4			

2.2.3: Policies

a) What policies are there which affect or influence your use and management of water, energy, and food production in your household/community? (**Please list)**

Numbering	WEF sector	Current policy	Explain how does each of the listed to the left affect use or management of water.
2.2.3.1	Water		
2.2.3.2	Energy		
2.2.3.3	Food production		

b) In your opinion what changes need to be made to improve the roles of the policies in supporting your effective and sustainable use and management of water, energy, and food production in your household/community? (**Please list**)

Numbering	Changes need to be made to improve the roles of the policies in supporting WEF nexus elements		
	Water	Energy	Food
2.2.3.4			

SECTION 3: FINANCIAL SUPPORT, EXTENSION AND ADOPTION

Section 3.1: WEF financing

Have you received any financing towards any of the following?

Numbering	WEF	Credit source	Yes/No	Specific Purpose on which credit was utilised	Any comment
3.1.1	Water development	Cooperative Bank Microcredit Family Local saving group Grant (specify)			
3.1.2	Energy development	Cooperative Bank Microcredit Family Local saving group Grant (specify)			
7.1.3	Food production	Cooperative Bank Microcredit Family Local saving group Grant (specify)			

Section 3.2: Communication channels and extension services on WEF technologies

For each of the information sources provide the frequency you have had in the last one year

Numbering	Source of information for each WEF	Source of information	Yes/ No	How frequent do you receive the information (for each source)
3.2.1	Energy smart technologies	Public extension Private extension Radio Newspaper Online Peers Scientific publication Autonomous (own effort)		Daily Weekly Monthly Quarterly Biannually Annually
3.2.2	Water Smart technologies	Public extension Private extension Radio Newspaper Online Peers		

		Scientific publication Autonomous (own effort)		
3.2.3	Land use for food production smart technologies	Public extension Private extension Radio Newspaper Online Peers Scientific publication Autonomous (own effort)		

Section 3.3: Players in WEF technology promotion and adoption

Numbering	**Smart technology**	**Specific WEF smart innovation**	**Who promotes**	**Constraints**	**Rank the constraints named (Use 1 for the most pressing)**
3.3.1	Energy	Solar Energy saving Wind Any Other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort)	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	
3.3.2	Water use	Water recycling Water harvesting/ roof harvesting Drip irrigation Hydroponics Any other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency International organisation Autonomous (own effort)	Initial investment cost Maintenance costs Lack of market Lack of knowhow High Cost of alternatives Lack Access to alternatives Any other	
3.3.3	Land use	Manuring Cover crops Mulching Zero tillage Climate manipulation /Green houses Any other	Public extension Private Extension NGO/ CSO/ CBO Research Organisation Government agency	Initial investment cost Maintenance costs Lack of market Lack of knowhow	

			International organisation Autonomous (own effort	High Cost of alternatives Lack Access to alternatives Any other	

Section 3.4: Factors influencing adoption of smart WEF technologies

What has influenced or likely to influence you adopt smart technologies?

Numbering	WEF Technology	Factor	Already influenced you? Yes/ no	Rank the influencer (Use 1 to n with 1 as the most important
3.4.1	Energy smart technologies	Knowledge/ education Finance Value for environment Social network Peers Family spillovers Market access Grant High returns Cost saving Reliability		
3.4.2	Water smart Technologies	Knowledge/ education Finance Value for environment Social network Peers Family spillovers Market access Grant High returns Cost saving Reliability		
3.4.3	Land use/ food production smart technologies	Knowledge/ education Access to financing Value for environment Social network Peers Family spillovers Market access Grant High returns Cost saving		

Section 3.5: Barriers to WEF smart technologies

Numbering	WEF resource	Barrier	Yes / No	Rank the barriers (Use 1 to n with 1 as the most important)
3.5.1	Energy smart technologies	Initial cost		
		Technical Knowhow		
		Government regulation and policies		
		Lack of information		
		Lack of capital/ credit		
		Lack of alternatives		
		High cost of alternatives		
		Any other		
3.5.2	Water smart technologies	Initial cost		
		Technical Knowhow		
		Government regulation and policies		
		Lack of information		
		Lack of capital/ credit		
		Lack of alternatives		
		High cost of alternatives		
		Any other		
3.5.3	Land use smart technologies	Initial cost		
		Technical Knowhow		
		Government regulation and policies		
		Lack of information		
		Lack of capital/ credit		
		Any other		

To ensure that the proposed mixed model approach is robust enough, Sections 8, 9 and 10 interview questions are open-ended questions so that in-depth information will be collected.

SECTION 4: WEF NEXUS TRADE-OFF AND SYNERGIES[3]

Numbering	Required to fill-in/Question	Instruction
8.1	What are the trade-offs (even potential completion) experienced while enhancing synergies towards attaining simultaneous WEF resource securities?	Please read the statements and ask the respondent to answer to their best ability.
8.2	What are the synergies required to attain simultaneous WEF resource securities?	
8.3	Practical experience in water, energy and food interlinkages	

SECTION 5: GENERAL KNOWLEDGE ON WEF NEXUS

Numbering	Required to fill-in/Question	Instruction
9.1	What is the meaning of WEF nexus approach?	Please read the statements and ask the respondent to answer to their best ability.
9.2	What do you understand by the term water security?	
9.3	What do you understand by the term renewable energy?	
9.4	What do you understand by the term food security?	
9.5	What do you understand by the term sustainability?	

SECTION 6: SUGGESTED WEF NEXUS SOLUTIONS

Numbering	Required to fill-in/Question	Instruction
10.1	What should be done to eradicate water insecurity?	Please read the statements and ask the respondent to answer to their best ability.
10.2	What should be done to eradicate energy scarcity (if any)?	
10.3	What should be done to eradicate food insecurity?	
10.4	What can be done to overcome the barriers impeding WEF nexus operationalisation?	

[3] Naidoo et al. (2021) Operationalizing the water-energy-food nexus through the theory of change.

		to miss in your diet/ can afford to miss without being concerned on daily/ periodically
11.1	Vegetables/ fruits	
11.2	Cereals/ pulses	
11.3	Meat/ milk/ eggs/ chicken	

APPENDIX B: RELATIONSHIP BETWEEN GENDER, AGE, EDUCATION, EMPLOYMENT STATUS AND ECONOMIC STATUS.

Village	Gender	%	Age	%	Education	%	Employment status	%	Economic status	%
Siloam	Female Males Missing	38.5 46.2 15.4	Under 20yrs 21030yrs 31040yrs 41050yrs 51060yrs Above 60yrs Missing	0.0 0.0 30.8 30.8 15.4 7.7 15.4	No schooling Primary Secondary TVET/College University Missing	0.0 0.0 53.8 23.1 7.7 15.4	Formal Informal Unemployed Retired Missing	30.8 23.1 23.1 0.0 23.1	002000 200104000 400106000 600108000 8001010000 Above 10000 Missing	30.8 0.0 0.0 0.0 23.1 7.7 15.4
Phadzima	Female Males Missing	64.3 28.6 7.1	Under 20yrs 21030yrs 31040yrs 41050yrs 51060yrs Above 60yrs Missing	0.0 0.0 14.3 14.3 14.3 50.0 7.1	No schooling Primary Secondary TVET/College University Missing	7.1 21.4 64.3 0.0 0.0 7.1	Formal Informal Unemployed Retired Missing	0.0 14.3 57.1 21.4 7.1	002000 200104000 400106000 600108000 8001010000 Above 10000 Missing	42.9 14.3 14.3 14.3 0.0 7.1 7.1
Khalavha	Female Males Missing	63.2 36.8 0.0	Under 20yrs 21030yrs 31040yrs 41050yrs 51060yrs Above 60yrs	5.3 21.1 26.3 21.1 15.8 10.5	No schooling Primary Secondary TVET/College University Missing	0.0 5.3 78.9 15.8 0.0 0.0	Formal Informal Unemployed Retired Missing	0.0 15.8 78.9 5.3 0.0	002000 200104000 400106000 600108000 8001010000 Above 10000	47.4 31.6 0.0 0.0 5.3 5.3
Sambandou	Female Males Missing	88.9 11.1 0.0	Under 20yrs 21030yrs 31040yrs 41050yrs 51060yrs Above 60yrs	0.0 5.6 22.2 22.2 16.7 33.3	No schooling Primary Secondary TVET/College University Missing	27.8 16.7 38.9 16.7 0.0 0.0	Formal Informal Unemployed Retired Missing	33.3 11.1 55.6 0.0 0.0	002000 200104000 400106000 600108000 8001010000 Above 10000	66.7 5.6 11.1 5,6 11.1 0.0
Malavuwe	Female	22.2	Under 20yrs	0.0	No schooling	0.0	Formal	0.0	002000	44.4

	Males	77.8	21030yrs	11.1	Primary	44.4	Informal	44.4	200104000	44.4
	Missing	0.0	31040yrs	11.1	Secondary	44.4	Unemployed	33.3	400106000	0.0
			41050yrs	22.2	TVET/College	11.1	Retired	11.1	600108000	0.0
			51060yrs	22.2	University	0.0	Missing	11.1	8001010000	0.0
			Above 60yrs	33.3	Missing	0.0			Above 10000	0.0
									Don't want to say	11.1
Tshakhuma	Female	15.0	Under 20yrs	5.0	No schooling	0.0	Formal employment		002000	50.0
	Males	85.0	21030yrs	5.0	Primary	10.0	Informal employment		200104000	15.0
	Missing	0.0	31040yrs	10.0	Secondary	65.0	Unemployed		400106000	5.0
			41050yrs	15.0	TVET/College	15.0	Retired		600108000	15.0
			51060yrs	40.0	University	10.0			8001010000	5.0
			Above 60yrs	25.0	Missing	0.0			Above 10000	0.0
									Don't want to say	10.0
Total										

APPENDIX C: WATER INNOVATION INNOVATIONS AND PRACTICES

Water Innovation technologies												
	Nzhelele River Catchment Areas						Luvuvhu River Catchment Areas					
	Siloam		Khalavha		Phadzima		Malavuwe		Sambandou		Tshakhuma	
	N	%	N	%	N	%	N	%	N	%	N	%
Whether rainwater is used or not	**8**	61.5	**13**	68.4	**10**	71.4	**6**	66.7	**10**	55.6	**10**	50
Whether groundwater is used or not	**4**	30.8	**0**	0	**0**	0	**0**	0	**0**	0	**3**	15
Whether water recycling is used or not	**5**	38.5	**6**	31.6	**4**	28.6	**5**	55.5	**4**	22.2	**5**	25
Whether water reducing loss is used or not	**1**	7.7	**1**	5.3	**0**	0	**0**	0	**0**	0	**1**	5

APPENDIX D: ENERGY INNOVATION INNOVATIONS AND PRACTICES

Energy Innovation technologies												
	Nzhelele River Catchment Areas						Luvuvhu River Catchment Areas					
	Siloam		Khalavha		Phadzima		Malavuwe		Sambandou		Tshakhuma	
	N	%	**N**	%	**N**	%	**N**	%	**N**	%	**N**	%
Whether NR is used or not	**13**	100	**19**	100	**14**	100	**9**	100	**18**	100	**20**	100
Indicate coal is used	**1**	7.7	**0**	0	**0**	0	**0**	0	**0**	0	**1**	5
Indicate if electricity is used	**12**	92.3	**19**	100	**14**	100	**9**	100	**18**	100	**19**	95
Indicate if firewood is used	**13**	100	**19**	100	**14**	100	**9**	100	**18**	100	**16**	80
Indicate if use paraffin	**0**	0	**0**	0	**1**	7.1	**1**	11.1	**0**	0	**2**	10
Whether R is used or not	**4**	30.8	**0**	0	**0**	0	**1**	11.1	**0**	0	**7**	35
Indicate if use Biogas	**0**	0	**0**	0	**0**	0	**1**	11.1	**0**	0	**3**	15
Indicate if solar is used	**4**	30.8	**0**	0	**1**	7.1	**0**	0	**0**	0	**5**	25
Indicate if use Wind	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0

APPENDIX E: FOOD INNOVATION INNOVATIONS, TECHNOLOGIES AND PRACTICES

Food Innovation technologies												
Nzhelele River Catchment Areas							Luvuvhu River Catchment Areas					
	Siloam		Khalavha		Phadzima		Malavuwe		Sambandou		Tshakhuma	
	N	%	**N**	%	N	%	N	%	N	%	N	%
Whether CA is used or not	**5**	38.5	**9**	47.4	**6**	42.9	**3**	33.3	**10**	55.5	**7**	35
Whether Smart irrigation Agriculture is used or not	**1**	7.7	**1**	5.3	**2**	14.3	**1**	11.1	**0**	0	**0**	0
Whether Sustainable intensification Agriculture is used or not	**3**	23.1	**2**	10.5	**0**	0	**1**	11.1	**2**	11.1	**3**	15
Whether Behaviour change interventions agriculture is used or not	**6**	46.2	**0**	0	**0**	0	**0**	0	**0**	0	**2**	10
Whether Disaster related insurance is used or not	**0**	0	**1**	5.3	**0**	0	**0**	0	**0**	0	**0**	0

APPENDIX F1: ETHICS CLEARANCE CERTIFICATE (WRC PROJECT)

ETHICS APPROVAL CERTIFICATE

RESEARCH AND INNOVATION
OFFICE OF THE DIRECTOR

NAME OF RESEARCHER/INVESTIGATOR:
Dr R Makungo

STAFF NO:
200595

PROJECT TITLE: Integrating water-energy-food nexus innovations and practices into policy, governance, and institutional frameworks for sustainable development in Vhembe District, Limpopo Province, South Africa.

ETHICAL CLEARENCE NO: FSEA/22/ES/16/2809

SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS

NAME	INSTITUTION & DEPARTMENT	ROLE
Dr R Makungo	UNIVEN, Earth Sciences	Investigator – Staff
Dr. EJ Mwendera	Clovita Consulting Services	Researcher
Prof K Nephawe	Ozone Agri Development Solutions Pty (Ltd)	Researcher

Type: **Staff Research**
Risk: **Minimal risk to humans, animals, or environment (Category 2)**
Approval Period: **September 2022 – September 2023**

The Animal, Environmental and Biosafety Research Ethics Committee (AEBREC) hereby approves your project as indicated above.

General Conditions
While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following.

- The project leader (principal investigator) must report in the prescribed format to the REC:
  - Annually (or as otherwise requested) on the progress of the project, and upon completion of the project
  - Within 48hrs in case of any adverse event (or any matter that interrupts sound ethical principles) during the course of the project.
  - Annually a number of projects may be randomly selected for an external audit.
- The approval applies strictly to the protocol as stipulated in the application form. Would any changes to the protocol be deemed necessary during the course of the project. The project leader must apply for approval of these changes at the REC. Would there be deviated from the project protocol without the necessary approval of such changes, the ethics approval is immediately and automatically forfeited.
- The date of approval indicates the first date that the project may be started. Would the project have to continue after the expiry date; a new application must be made to the REC and new approval received before or on the expiry date.
- In the interest of ethical responsibility, the RECs retains the right to:
  - Request access to any information or data at any time during the course or after completion of the project,
  - To ask further questions; Seek additional information; Require further modification or monitor the conduct of your research or the informed consent process.
  - withdraw or postpone approval if:
  - Any unethical principles or practices of the project are revealed or suspected.
  - It becomes apparent that any relevant information was withheld from the REC or that information has been false or misrepresented.
  - The required annual report and reporting of adverse events was not done timely and accurately,
  - New institutional rules, national legislation or international conventions deem it necessary

ISSUED BY:
UNIVERSITY OF VENDA, RESEARCH ETHICS COMMITTEE
Date Considered: September 2022

Name of the AEBREC Chairperson of the Committee: Prof Irene Barnhoorn

Signature: ....

UNIVERSITY OF VENDA
OFFICE OF THE DIRECTOR
RESEARCH AND INNOVATION
2022 -10- 03
Private Bag X5050
Thohoyandou 0950

University of Venda
PRIVATE BAG X5050, THOHOYANDOU, 0950\ LIMPOPO PROVINCE\ SOUTH AFRICA
TELEPHONE (015) 962 8504/8313 FAX (015) 962 9060
"A quality driven financially sustainable, rural-based Comprehensive University"

APPENDIX F2: ETHICS CLEARANCE CERTIFICATE (CURRENT STUDY)

ETHICS APPROVAL CERTIFICATE

ETHICS APPROVAL CERTIFICATE

**FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE
RESEARCH ETHICS COMMITTEE**

NAME OF RESEARCHER/INVESTIGATOR: P MPHAPHULI

STAFF/STUDENT NO: 17004331

PROJECT TITLE: Assessing sustainable water, energy and food (WEF) nexus smart innovations and practices in Luvuvhu and Nzhelele River Catchments Areas, South Africa, Limpopo Province.

ETHICAL CLEARENCE NO: FSEA/23/ES/13

SUPERVISORS/ CO-RESEARCHERS/ CO-INVESTIGATORS

NAME	INSTITUTION & DEPARTMENT	ROLE
Prof R Makungo	University of Venda, Earth Sciences	Supervisor
Dr T Madzivhandila		Co-Supervisor
Prof KD Musetsho	University of Venda, Earth Sciences	Co-Supervisor

Type: **Student research**

Risk: **Minimal risk to humans, animals, or environment (Category 1)**

Approval Period: **January 2024 – January 2026**

The Faculty Research Ethics Committee (FREC) of the Faculty of Science, Engineering and Agriculture hereby approves your project as indicated above.

University of Venda

PRIVATE BAG X5050, THOHOYANDOU, 0950, LIMPOPO PROVINCE, SOUTH AFRICA
TELEPHONE (015) 962 8394/8107. FAX (015) 962 8000
"A quality driven financially sustainable, Comprehensive University"

ETHICS APPROVAL CERTIFICATE

General Conditions

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following.

- **The project leader (principal investigator) must report in the prescribed format to the REC:**
  - **Annually (or as otherwise requested) on the progress of the project, and upon completion of the project**
  - **Within 48hrs in case of any adverse event (or any matter that interrupts sound ethical principles) during the project.**
  - **Annually, research projects may be randomly selected for auditing.**
- **The approval applies strictly to the protocol as stipulated in the application form. Should a change to the protocol be deemed necessary during the project, the project leader must apply for approval of these changes before their implementation. Should there be a deviation from the study protocol, without the necessary approval for the change, the ethics approval is automatically forfeited.**
- **The date of approval indicates the earliest date that the project may begin. Should the project have to continue after the expiry date; a new application must be made, and a new approval received before or on the expiry date.**
- **In the interest of ethical responsibility, the FREC retains the right to:**
  - **Request access to any information or data at any time during the course or after completion of the project,**
  - **To ask further questions; Seek additional information; Require further modification or monitor the conduct of your research or the informed consent process.**
  - **withdraw or postpone approval if:**
  - **Any unethical principles or practices of the project are revealed or suspected.**
  - **It becomes apparent that relevant information was withheld from the REC or that information has been false or misrepresented.**
  - **The required annual report and reporting of adverse events was not done timely and accurately,**
  - **New institutional rules, national legislation or international conventions deem it necessary**

ISSUED BY:
FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE RESEARCH ETHICS COMMITTEE

Chairperson: Prof. L.C Murulana

University of Venda

PRIVATE BAG X5050, THOHOYANDOU, 0950, LIMPOPO PROVINCE, SOUTH AFRICA
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APPENDIX G: INFORMED CONSENT DOCUMENT

RESEARCH ETHICS COMMITTEE

UNIVEN Informed Consent

LETTER OF INFORMATION

Title of the Research Study : Assessing sustainable water, energy and food (WEF) nexus smart innovations, technologies and practices in Luvuvhu and Nzhelele River catchments areas, Vhembe District Municipality, Limpopo province, South Africa.

Principal Investigator/s/ researcher : (Mphaphuli Phindulo)

Co-Investigator/s/supervisor/s : (*Rachel Makungo, PhD*)
(Khangwelo Desmond Musetsho. PhD)
(Tshilidzi Madzivhandila, PhD)

Brief Introduction and Purpose of the Study:

Outline of the Procedures : (*Responsibilities of the participant, consultation/interview/survey details, venue details, inclusion/exclusion criteria, explanation of tools and measurement outcomes, any follow-ups, any placebo or no treatment, how much time required of participant, what is expected of participants, randomization/ group allocation*)

The target communities for involvement in the study will be rural communities in Vhembe District living in rural settlements with low-income, fast-growing peri-urban centers and small-scale farmers. We will use the random sampling table to select a representative sample from the population. We will use a factual questionnaire to help gather information. During this stage, we will also identify key stakeholders who ought to be active or participate in the focus group discussion.

Risks or Discomforts to the Participant: (*Description of foreseeable risks or discomforts to for participants if applicable e.g. Transient muscle pain, VBAI, post-needle soreness, other adverse reactions, etc.)*

The risk of infection/transmission of COVID-19 will be minimised by adhering to adjust level 1 COVID-19 protocol.

Benefits : (*To the participant and to the researcher/s e.g. Publications*)

The results of the study are intended to generate viable WEF nexus smart innovations and practices which help with effective implementation of WEF nexus approach for sustainable development at household level.

Reason/s why the Participant May Be Withdrawn from the Study: (*Non-compliance, illness, adverse reactions, etc. Need to state that there will be no adverse consequences for the participant should they choose to withdraw)*

Participants may withdraw from the study only on their own free will.

Remuneration : None*)*

Costs of the Study : (None

Confidentiality : Information collected during the interviews will be kept in confidence by the project team members and will not be shared without the consent of the participants. Care will also be taken to ensure that the research findings are not presented in a way that would enable the identification of or prejudice a participant.

Research-related Injury : No research related injuries are expected to happen.

Persons to Contact in the Event of Any Problems or Queries:

(Rachel Makungo) Please contact the researcher (063 642 0380), my supervisor (067 997 7893) or the University Research Ethics Committee Secretariat on 015 962 9058. Complaints can be reported to the Director: Research and Innovation, Snr Prof GE Ekosse on 015 962 8313 or Georges Ivo.Ekosse@univen.ac.za

General:

Potential participants must be assured that participation is voluntary and the approximate number of participants to be included should be disclosed. A copy of the information letter should be issued to participants. The information letter and consent form must be translated and provided in the primary spoken language of the research population

CONSENT

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, (*name of researcher*), about the nature, conduct, benefits and risks of this study - Research Ethics Clearance Number: _,
- I have also received, read and understood the above written information (*Participant Letter of Information*) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerized system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

Full Name of Participant Date Time Signature

I, ……………………… …………… ………… ……………………..

(*Name of researcher*) herewith confirm that the above participant has been fully

Informed about the nature, conduct and risks of the above study.

Full Name of Researcher

……………………… Date………………. Signature…………………

Full Name of Witness (If applicable)

……………………. Date ………………. Signature…………………..

Full Name of Legal Guardian (If applicable)

………………… Date……………… Signature……………………

Please note the following:

Research details must be provided in a clear, simple and culturally appropriate manner and prospective participants should be helped to arrive at an informed decision by use of appropriate language (grade 10 level- use Flesch Reading Ease Scores on Microsoft Word), selecting of a non-threatening environment for interaction and the availability of peer counseling (Department of Health, 2004)

If the potential participant is unable to read/illiterate, then a right thumb print is required and an impartial witness, who is literate and knows the participant e.g. parent, sibling, friend, pastor, etc. should verify in writing, duly signed that informed verbal consent was obtained (Department of Health, 2004).

If anyone makes a mistake completing this document e.g. a wrong date or spelling mistake, a new document has to be completed. The incomplete original document has to be kept in the participant's file and not thrown away, and copies thereof must be issued to the participant.

References:

Department of Health: 2004. *Ethics in Health Research: Principles, Structures and Processes*

http://www.doh.gov.za/docs/factsheets/guidelines/ethnics/

Department of Health. 2006. *South African Good Clinical Practice Guidelines*. 2nd Ed. Available at:

http://www.nhrec.org.za/?page_id=14

APPENDIX H: LANGUAGE EDITING PROOF READING

EDITOR'S LETTER

School of Languages, Faculty of Humanities, North-West University
Innocent.Zitha@nwu.ac.za *Office Tel : 0183892655*

To whom it may concern

Dear Sir/Madam

This is to authenticate that I, Zitha Innocent, have proofread and edited a dissertation for a MSc degree in the Department of Hydrology and Water Resources in the Faculty of Science, Engineering and Agriculture at the University of Venda entitled **Assessing sustainable water, energy and food (WEF) nexus smart innovations, technologies and practices in Luvuvhu and Nzhelele River catchments areas, Vhembe District Municipality, Limpopo province, South Africa**

By

MPHAPHULI PHINDULO

17004331

I have meticulously and comprehensively inspected this thesis for consistency, coherence, and correctness of language use, ensuring proper register usage and citations. I have suggested several amendments, which were communicated to the student for consideration and implementation. The student has undertaken to effect these amendments before this research project is finally submitted.

Date: **29/01/2025**

BA Hons (English), MA (English), PhD (current studies), Lecturer (English) @ North-West University