Climate change impacts on the nexus between water, energy and food resources: The cases of Narok County in Kenya and Vhembe District Municipality, in South Africa

by

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Submitted in partial fulfillment of the requirement of the degree

DOCTOR OF PHILOSOPHY in METEOROLOGY

DEPARTMENT OF GEOGRAPHY, GEOINFORMATICS AND METEOROLOGY

FACULTY OF NATURAL AND AGRICULTURAL SCIENCES

UNIVERSITY OF PRETORIA

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Year: 2025

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DECLARATION

I Nosipho Ntombani Zwane declare that this dissertation that I am submitting for the degree Doctor of Philosophy in Meteorology at the University of Pretoria is my own work and has not been submitted by me for a degree at any tertiary institution. I have used Harvard as the convention for citation and referencing.

SIGNATURE …………….. DATE 22 May 2025 …………………

ABSTRACT

The current and predicted increase in global demand for the Water-Energy-Food (WEF) resources as well as the inherent links between the WEF sectors and sustainable development, the WEF nexus is rapidly being recognized as a method to manage sustainable development effectively. Many African countries still have demand and accessibility challenges to WEF resources. For this reason, a comparative study of two different sites (Narok County and Vhembe District Municipality), yet exhibiting similar socio-economic, environmental and technological circumstances was undertaken. In the present study, we considered 218 questionnaire responses, which we analyzed using the partial least squares - Structural Equation Modelling (SEM) based on the WEF nexus constructs. Two hypotheses were formulated: 1) Null Hypothesis (H0) – No interdependencies exist between the state of climate and the WEF resources, 2) Alternative Hypothesis (Ha) – Interdependencies exist between the state of climate and WEF resources. Results show that the alternative hypothesis (Ha) is true, demonstrated by the descriptive statistics indicating p-values < 0.05 for both the t-test and the Bartlet test. Furthermore, results from the multi-regression model based on data from both sites showed p-values < 0.05 and higher adjusted r-squared values, suggesting a better fit. The communities in both study sites agree that the regions have experienced a scarcity of WEF resources due to climate change. The results show that climate change is an intrinsic part of developmental options for the sustainable livelihood of both study sites in line with the 2030 UN agenda on sustainable development goals targets. The results illustrate that both study sites share similar socio-economic and environmental challenges. Moreover, future changes in rainfall and temperature projections indicated that constraints in the scarcity of WEF resources will be exacerbated and this will increase the vulnerability in both study sites. Thus, sustainable management of natural resources that is people and planet centric is crucial to climate change adaptation and mitigation, social justice, equity, and inclusion. The SEM results showed with significant confidence that the water, energy and food sectors are closely interconnected, and the impact on climate and sustainability is significantly different. Food has a direct positive impact on climate and sustainability, while both water and energy have an indirect negative impact. Moreover, for all the relationships explored, climate indicated a significant direct link to sustainability. Since in most underdeveloped countries, sustainable development and societal well-being heavily rely on goods and services derived from the natural resources and the environment, this study contributes to the nexus modeling research

field by introducing SEM as an innovative methodology over a single equation modeling framework in analyzing variables that have complex interrelationships and facilitates advanced WEF Nexus resource governance. Moreover, this study explored alternative options for community resilience to climate change.

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PREFACE

Africa accounts for the smallest amount of greenhouse gas emissions in contrast to the developed countries, yet the continent struggle the most from changing climate and remains most vulnerable due to its low adaptive capacity. The Intergovernmental Panel on Climate Change (IPCC) sixth report projects climate change over three future periods: 2021 – 2040, 2041 – 2060 and 2081 - 2100. In Africa the climate projections indicate that the continent will endure increase in mean and extreme temperatures. Rainfall remains, a difficult parameter with high uncertainty, however generally some countries are projected to have an increase in rainfall, while others will have a decreased in rainfall, which is signal to both extreme floods and droughts. There are still issues with demand and accessibility for Water-Energy-Food (WEF) resources in many African countries. Because of this, a comparative analysis of two distinct sites, Narok County and Vhembe District Municipality that shared comparable socioeconomic, environmental, and technological conditions was conducted.

Chapter one provides a brief background and overview of the study. The aim, objectives and scope of the study are also described.

Chapter two captures the data used and their sources, the research methodology and method of analysis. The schematic framework of the research is presented and discussed. Chapter 2 focuses on the questionnaire distribution statistics in both the study sites, the WEF resources stature and reviews the interdependences of WEF resources under the current state of climate. Chapter three investigates potential synergy between driving variables (climate change and sustainability) and WEF resources using structural equation modeling (SEM) technique to explain the explicit or implicit consequences of climate change on WEF resources in the study sites. Chapter four investigates how climate change will interfere with the interlinkages of the WEF resources in the study areas through examining the potential effects of projected rainfall and temperature changes in future and the impact thereof on the water, energy, and food resources. Furthermore, integrates a modeling framework designed to depicts the perceptions of future climate change impacts on communities based on questionnaires and first-hand account. Lastly, the general conclusions, recommendations and future work are given in Chapter 5.

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LIST OF PUBLICATIONS

The publications listed have been published and or submitted in/to various peer-reviewed journals as part of this work and as contribution to the Water Research Commission funded project reports.

Lead author: Published (Energies)

1. **Zwane, N**.; Tazvinga, H.; Botai, C.; Murambadoro, M.; Botai, J.; deWit, J.; Mabasa, B.; Daniel, S.; Mabhaudhi, T. A Bibliometric Analysis of Solar Energy Forecasting Studies in Africa. *Energies* 2022, 15, 5520. https://doi.org/10.3390/en15155520

Lead author: Published (Sustainability)

2. **Zwane, N**.; Botai, J.O.; Botai, C, M.; Mabhaudhi, T. Sustainability of the linkages between the WEF resources based on structural equation modelling under changing climate: A case study of Narok County (Kenya) and Vhembe District Municipality (South Africa). *Sustainability* 2024, 16, 9689. https://doi.org/10.3390/su16229689

Lead author: Published (Water)

3. **Zwane, N**.; Botai, J.O.; Nozwane, S.H.; Jabe, A.; Botai, C.M.; Dlamini, L.; Nhamo, L.; Mpandeli, S.; Peja, B.; Isaac, M.; Mabhaudhi, T. Analysis of the projected climate impacts on the interlinkages of water, energy and food nexus resources in Narok County, Kenya and Vhembe District Municipality, South Africa. *Water* 2025, 17, 1449. https://doi.org/10.3390/w17101449

Co-author: Publications contributed to

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Co-author WRC Report contributed to

1. Joel Botai, Masinde Muthoni, Erick Wamiti, Christina Botai, Katlego Ncongwane, Miriam Murambadoro, Michael Mengistu, Henerica Tazvinga, Abiodun Adeola, Thabo Makgoale, **Nosipho Zwane**. Climate Change and Water Security: Developmental perspectives for water-linked sectors in a future climate for Africa. *Water Research Commission Report No. 3068/1/23* published in April 2023
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ACKNOWLEDGEMENT

I would like to express my utmost gratitude to the following people for making this work a success.

- Dr. Joel Botai for affording me the opportunity to work with him, for his invaluable input and support during this research. I am thankful for his constant availability, guidance, assistance, mentorship and sharing his profound expertise in the field of meteorology and applied climatology. Moreover, I am thankful for sharing his expertise for me to advance my research skills and advance with R coding, managing and analysis of big and variable data. I am grateful for his patience and encouragement throughout the project. Thank you for pouring into my cup and landing a hand in shaping my career and profession.
- Prof. Tafadzwanashe Mabhaudhi for his guidance, supervision and continual reviews and feedback throughout the project. Moreover, for assistance with financial support through The Sustainable and Health Food Systems - Southern Africa (SHEFS-SA) Programme, supported by the Wellcome Trust [Grant No 227749/Z/23/Z].
- The financial support of the Water Research Commission of South Africa, grant numbers C2019/2020-00017. I am thankful for the opportunity of being one of the PhD students sponsored by the project which was biliteral between the two countries and required travel to the field.
- Thank you to South African Weather Service for providing an environment for me to conduct my studies, computational facilities, and for the data used in this study.
- Thank you to the UP Postgraduate Doctoral Bursary which made it possible for me to purchase a laptop for my studies.
- In conclusion, I give all the Glory to the Lord and a big thank you to my family for constant love, encouragement and support throughout everything. To my late Father, I miss you daily. You're passing in the middle of this qualification broke me, thank God for the strength to carry on, I know you are proud of me.

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LIST OF ABBREVIATION

AHP – Analytic Hierarchy Process

ALF – Analytical Livelihood Framework

CMIP5 – Coupled Model Intercomparison Project Phase 5

GCM – Global Climate Model

IPCC – Intergovernmental Panel on Climate Change

KEWI – Kenya Water Institute

MCA – Multiple Correspondence Analysis

RCA4 – Rossby Centre Regional Atmospheric Model

SAWS – South African Weather Service

SDG – Sustainable Development Goals

SEM – Structural Equation Modelling

TAHMO – Trans-African Hydro-Meteorological Observatory

UN – United Nations

VDM – Vhembe District Municipality

WEF – Water-Energy-Food

WRC – Water Research Commission

CHAPTER ONE: BACKGROUND INFORMATION

This chapter provides a brief background and overview of the study. The aim, objectives and scope of the study are also described.

1.1. INTRODUCTION

Globally it has been clear that climate change is an inevitable process, having major impacts on water, energy and food resources (Thompson et al., 2010, Feulner, 2015, Muluneh, 2021, Leck and Simon, 2018, Senzanje et al., 2023). Numerous studies (e.g., Kenway et al., 2011, Endo et al., 2017, Zaman et al., 2017, Mabhaudhi et al., 2018, Mpandeli et al., 2018, Kulat et al., 2019) have been conducted to understand the water-energy-food (WEF) nexus. According to Kenway et al (2011), the suggested broad definition of WEF nexus addresses the interconnection or cause-effect relationship between water, energy and food. In a study by Keskinen et al (2016), the WEF nexus can be viewed as 1) an analytical tool as it systematically uses quantitative or qualitative methods to understand connections in water, energy and food systems; 2) a conceptual framework focusing on understanding of WEF linkages to promote coherence in policymaking and enhance sustainability and 3) problem framing and promoting cross-sectoral collaboration.

Water, energy and food are essential resources for human well-being, poverty reduction and sustainable development. The projected increase in demand for these resources in the near future is due to population growth, urbanization, changes in diets, cultural and technological changes and changing climate among others (Mabhaudhi et al., 2019). Recurrence in these changes is expected to exert pressure on the already scarce and depleting natural resources, threatening their sustainability and undermining the resilience of communities.

Africa has a relatively dense population with high competition of natural resources among the people. According to Mabhaudhi et al (2019), 60% of southern Africa's population lives in rural areas with limited access to basic services and facilities such as clean and safe water, clean and affordable energy and balanced nutritious diets. In light of the present growing natural resource scarcity, there is a general recognition that water, energy and food security supply form the basis of a resilient economy.

The term nexus gained popularity and attention at Rio+20 and included systems approach for water, energy, land and food security for sustainable development. According to Prasad et al

(2012), understanding and analyzing the WEF nexus will create opportunities to increase resource use efficiency and will ensure sustainable access to water, energy and food while enhancing policy coherence. The WEF nexus is evidence-based, interactive and ensures improvements in livelihoods and sustainability of resources for human well-being.

A review of the WEF nexus research in Africa (Botai et al., 2021) using a bibliometric science mapping and content analysis of WEF nexus scientific publication trends, conceptual, intellectual, social structures and the inherent paradigmatic shifts in the body of knowledge in Africa showed that the WEF nexus scholarship expanded since 2013, particularly the conceptual, intellectual and social structure. Furthermore, the review pointed to the emergence of hot themes which include modeling and optimization, climate variability and change, sustainability of natural ecosystem services and sustainable development and livelihoods. Even though the WEF nexus is praised for promoting integrated resource management and systems thinking, it has faced criticism for being overly conceptual with inadequate practical application (Purwanto et al., 2021). Moreover, the critics opine that the WEF Nexus approach lacks standardized methods and relies on data that are often unavailable, particularly in developing countries. Additionally, the WEF Nexus approach may fail to adequately address local issues and ignore important governance concerns like institutional and political power dynamics. Despite its aim to break down silos, sectoral fragmentation remains a challenge. Furthermore, the WEF Nexus tends to focus on efficiency and trade-offs, sometimes neglecting environmental sustainability and social equity (Purwanto et al., 2021 and Li et al., 2025).

In order to promote rural resilience and sustainable livelihood, a shift from silo use and allocation of WEF resources is necessary. Studies focusing on livelihood generally refer to sustainable rural livelihood framework approach which emphasizes how people use their assets to come up with livelihood strategies (Carney, 2003). A WEF nexus for the resilience of rural communities' framework under climate change can be developed. This framework can be linked with the widely used sustainable rural livelihood framework as an assessing, monitoring and evaluating resource use and social development tool. According to Simpson and Jewitt (2019), the WEF nexus is concerned with simplifying human understanding of the complex interconnection among the WEF resources and ensuring resource sustainability and security. The WEF nexus approach is foreseen to give pathways that will transform rural livelihoods and ensure their resilience (Mabhaudhi et al., 2016).

A study by Mabhaudhi et al (2019) stipulated that over 240 million people in sub-Saharan Africa do not have access to nutritious food. Extreme weather events such as floods and droughts are observed to increase poverty and compromise human health and well-being. Small-holder farmers contribute the most to agricultural production, however, they do not have access to resources to adapt to the changing climate. The WEF nexus can play a significant role in climate change adaptation as it offers cross-sectoral mitigation and adaptation opportunities to harmonise interventions and build resilience (Nhamo et al., 2018).

The WEF nexus is a decision and management tool to better rural livelihoods through integrated resource distribution, planning and management and WEF nexus ensures inclusive socio-economic transformation and development, and addresses sustainable development goals (SDGs) 2, 3, 6 and 7 (Mathetsa et al., 2019). In South Africa and in Kenya water availability and supply drives both electricity generation and food production. Energy on the other hand is one of the most critical drivers of water treatment and distribution (Mathetsa et al., 2019). This points to the complex interlinkage of these systems. Currently in South Africa a WEF nexus analytical model based on the Analytic Hierarchy Process (AHP) was developed by Nhamo et al (2019) and the WEF nexus analytical livelihoods framework (ALF) was developed in study by Mabhaudhi et al (2019). The WEF nexus ALF is a system approach that analyses and assesses the interactions between the natural environment and the biosphere by facilitating more coordinated management and monitoring of resources.

Compared to affluent nations, Africa emits the least amount of greenhouse gases, yet it suffers the most from climate change and is still most vulnerable because of its limited ability to adapt. The IPCC sixth assessment report has reported that the climate projections in Africa indicate that the continent will endure an increase in mean and extreme temperatures (IPCC, 2021). Moreover, in African some countries are projected to have an increase in rainfall, while others will have a decrease in rainfall. These climate projections indicate that Africa is prone to extreme heat with increased warming days. Furthermore, Africa is set to experience both extreme hydrological tails of floods and droughts events. The present study was sponsored by the Water Research Commission (WRC) under auspices of bilateral collaboration that required careful selection of the study sites with similar environmental and socio-economic characteristics, hence the choice of Kenya (Narok County) and South Africa (Vhembe District Municipality, Limpopo province). The present study investigates how climate change interferes with the interlinkages of the water, energy and food resources in Kenya (Narok County) and South Africa (Vhembe District Municipality, Limpopo province). Moreover, develop on the WEF nexus ALF to WEF nexus modelling framework to assess resource utilization and resilience in rural communities in South Africa and Kenya under changing climate, in line with achieving the 2030 global agenda of SDGs, by providing solutions on how to best build resilient rural communities and enhance sustainable rural livelihoods. The interlinkages among variables relating to the WEF resources in the two study sites were evaluated using the Multiple Correspondence Analysis, the WEF Matrix and the Network Analysis based on a desktop analytic study and survey questionnaire. The present study sort to introduce 1) SDGs into the system 2) adding climate scenarios and 3) develop a modelling framework to demonstrate the causal linkages between WEF resources. Studies on WEF nexus research on the study sites have been in nascent stage. Therefore, this work contributes to the body of knowledge of comparative studies of WEF nexus research

1.2. STUDY RATIONALE

The study is motivated by the fact that WEF nexus has received increasing attention within science and international politics by promoting integrated resource governance. Observed nowadays there is major decrease in natural resources, mainly due to increasing population and climate change and variability. The observed scarcity of natural resources has led to water, energy and food insecurity, linked with human, economic and environmental instability.

The foreseeable high demand of primary resources has led to many countries in Africa to look for innovative solutions. In this regard the WEF nexus is considered by the scientific community to have a holistic approach in terms of dynamic linkages between water, energy and food resources management. This study seeks to test the two hypotheses below: -

1) Null Hypothesis (H0) – No interdependencies exist between the state of climate and the WEF resources.
2) Alternative Hypothesis (Ha) – Interdependencies exist between the state of climate and WEF resources.

The study seeks to prove if there is no (H0) or there is (Ha) interdependence between the state of climate and WEF resources. The WEF nexus concept is not new, it has been discussed in academia as well as at policy level. There is evidence around the world that WEF resources shortage often results in conflict, political instability as well as livelihood insecurity (Walker, 2020). The significance of the WEF nexus approach became apparent when social structures and the environment changed, putting more strain on already existing systems and emphasizing the relationship and trade-offs between sectors (Jones-Crank et al., 2024).

The present study will contribute towards expanding the research domain and the body of knowledge by uncovering the relationship and tradeoffs between WEF nexus resources under changing climate. Moreover, the present study can be used by the government to inform policy, especially in the current climate variability and climate change. The WEF nexus is still theoretical to policymakers, and its relevance is not well vested in society. The analysis from the present study provides recommendations for policy and decision makers in scaling up and implementing the WEF nexus approach. To achieve sustainable development within the WEF sectors, this study avers that an integrated approach encompassing political systems, various stakeholders and role-players jointly work together in order define and derive appropriate trade-offs with the WEF resources value chain especially in current changing climate. Furthermore, it is recommended that integration of the institutions mandated with policy making and implementation of WEF-nexus approaches be strengthened. Lastly, it is hoped that the study brings to the fore the important value of wide stakeholder participation prioritizing citizens to promote knowledge sharing, bottom-up solutions, and conflict resolution.

1.3. AIM AND OBJECTIVES

The main aim of the study was to investigate the climate change impact on the nexus between water, energy and food resources using Narok County (Kenya) and Vhembe District Municipality (South Africa) as case studies. The following objectives aided the aim of the study.

a) Assess the Interdependencies of Water, Energy and Food Nexus Resources in Narok County, Kenya and Vhembe District Municipality, South Africa under current state of climate.
b) To determine the sustainability of the linkages between the WEF resources based on Structural Equation Modelling under changing climate in Narok County, Kenya and Vhembe District Municipality, South Africa
c) Determine the level of interference that the projected climate has on the interlinkages of Water, Energy and Food Nexus in Narok County, Kenya and Vhembe District Municipality, South Africa.

1.4. RESEARCH QUESTIONS

There have been many theoretical and conceptual frameworks developed on the topic of WEF nexus and its alignment to sustainable development goals internationally and nationally. This study seeks to address the following specific questions that are inexhaustive in the literature: -

a) What are the comparative interdependencies of the WEF nexus resources under changing climate in the two study areas?
b) Does sustainable management of natural resources exist across the study areas that is people centric, responsive to climate change adaptation and mitigation, social justice, equity and inclusion?
c) How will future climate change interfere with the interlinkages of the WEF resources in the study areas?

It is significant for these questions to be answered to enable the research community on WEF nexus to broaden the scope to include the state of climate, climate variability and the change thereof in association with WEF resources in rural communities.

CHAPTER TWO: THE INTERDEPENDENCIES OF WATER, ENERGY AND FOOD NEXUS RESOURCES IN NAROK COUNTY (KENYA) AND VHEMBE DISTRICT MUNICIPALITY (SOUTH AFRICA) UNDER CHANGING CLIMATE.

This chapter outlines the data used and their sources, the research methodology and method of analysis. The schematic framework of the research is discussed. The chapter focuses on the questionnaire distribution statistics in both the study sites, the WEF resources stature and reviews the interdependences of WEF resources under the current state of climate.

2.1. INTRODUCTION

Over the past few decades, sustainable resource management has grown to be a significant issue worldwide. This global challenge is worsened by the growing demand for natural resources brought on by population and economic growth, which will also affect the achievement of the Sustainable Development Goals (SDGs) (SDGs, UN, 2015). Even with the implementation of programs like the 2030 Agenda for Sustainable Development Goals (UN, 2015), food, water, and energy insecurity persist in many African developing nations. Water, energy and food resource systems are intrinsically interconnected and are central to the global sustainability challenges (Nerini et al., 2017). Recently the water-energy-food (WEF) nexus has gained attention with specific focus to better comprehend the intricate relationships between various resource systems. Although the linkages between the food, energy, and water systems are not new, the idea gained popularity in 2011 through the World Economic Forum and the Bonn conference on Water, Energy, and Food Security (Hoff, 2011). Water, energy, and food linkages, synergies, and trade-offs are all taken into account by the WEF Nexus, a systems-based approach. The WEF nexus is a systems-based approach that considers the interactions, synergies and trade-offs among water, energy and food. According to Bazilian et al (2011), the WEF concept precisely recognises water, energy, and food systems as both interconnected and interdependent. The WEF nexus is closely aligned with the SDGs, particularly SDGs 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy). Several studies (Mpandeli et al., 2018, Bazilian et al., 2011; van Vuuren et al., 2012) have opined that the WEF nexus is one of the integrated new approaches and solutions to climate change, variability and adaptation, which is driven by energy use and land-use changes.

A study by Keskinen et al (2016) and Nhamo et al (2020) reported that the WEF nexus can be viewed as 1) an analytical tool because it used both quantitative and qualitative methods to understand the interlinkages between water, energy and food systems; 2) a conceptual framework (which is one of the common view thus far), that make use of knowledge of WEF interlinkages to improve sustainability and encourage coherence in policymaking; 3) a discourse, considering that the concept can be used for problem framing and promoting cross-sectoral collaboration. Research findings on the WEF nexus concept (Leck et al., 2015; Nhamo et al., 2018; Nhamo et al., 2020; Mabhaudhi et al., 2019; Kulat et al., 2019; Botai et al., 2021), its interpretation (Nhamo et al., 2018; Nhamo et al., 2020; Mabhaudhi et al., 2019), novelty (Albrecht et al., 2018), analytical tools and methods (Endo et al., 2015; Albrecht et al., 2018; Wiegleb and Bruns, 2018; Nhamo et al., 2018; Mabhaudhi et al., 2019; Nhamo et al., 2020), and criticism (Cairns and Krzywoszynska, 2016; Simpson and Jewitt, 2019) have grown quickly, demonstrating the nexus approach's intrinsic capacity to aid in the achievement of SDGs.

According to Botai et al (2021), studies on WEF nexus has gained popularity among scientists and policymakers thereby pointing water as the central element because originally the concept of WEF nexus was developed within the water centric research projects. In South Africa, since the year 2011, the Water Research Commission (WRC) has been championing the WEF nexus approach. To further develop and improve the WEF nexus literature, three studies (Newell et al., 2019; Chen et al., 2019; Opejin et al., 2020) have been carried out worldwide on bibliometric study of the WEF nexus and the linkages between the WEF systems. These studies have demonstrated how widely WEF nexus research has spread. In Africa there are limited WEF nexus studies available such as Botai et al (2021), which conducted a bibliometric analysis on the state-of-the-art WEF Nexus assessment globally and in Africa mainly focusing on eastern and southern Africa.

Although the WEF nexus concept holds great potential, numerous obstacles have hindered its application at various spatiotemporal scales. These difficulties are ascribed to a number of factors, including the overall value-chain translation of the WEF nexus concept from theory to practice, the lack of trustworthy tools and models, the existing knowledge gaps in understanding the interlinkages of WEF resources, and the absence of the data required to develop and test such technologies. This study thus reviews the WEF nexus resources in Narok County, Kenya and VDM, South Africa to map and understand their interdependencies under the current state of climate and further promote cross-sectoral linkages at local level for sustainable development.

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2.2. MATERIALS AND METHODS

2.2.1. Study Areas

The two study sites were selected given the socio-economic similarities and environmental challenges. The VDM (Figure 1) is in the northern part of Limpopo, demarcated by the Capricorn and Mopani District Municipalities to the eastern and western directions respectively. The VDM covers approximately 27 969 148 km^2 of land, divided by four local municipalities as follows, Makhado 8310.586 km^2, Thulamela 2 893.936 km^2, Musina 11 297.41 km^2 and Collins Chabane 5 467.216km^2 (Vhembe District Municipality, 2020/21 IDP review). The VDM is located within one of the largest river basins in Southern Africa, the Limpopo River basin which covers an area of 416 296km^2, spreading over four countries (South Africa 45%, Botswana 19%, Mozambique 21% and Zimbabwe 21%). The VDM is characterized as subtropical region by the Köppen-Geiger climate classification, with annual rainfall of 500mm between October and March. Moreover, the district frequently experiences minimum temperatures of 10°C and maximum temperatures of up to 40°C. Furthermore, the region frequently experiences droughts, fires and floods particularly in the semi-arid regions of Thulamela and Musina Local Municipality (Vhembe District Municipality. 2017/18-2021/22 Integrated Development Plan IDP, 2019). The rural community in VDM is faced with several challenges including high rate of illiteracy, unemployment, poverty, poor telecommunication, lack of agricultural produce market, lack of agro-processing industries, ageing water infrastructure (mostly asbestos pipelines), shortages of reliable water resources and inequality of electricity supply (Vhembe District Municipality, 2020/21 IDP review).

In Kenya, the selected study site is the Narok County (Figure 2) in southwestern Kenya. Narok County is one of the rural countries in Kenya (Asige and Omuse, 2022). The Narok County has two rainy seasons with short rains (occurring from late October to December) averaging 500mm and long rains (March to May) averaging 1899mm per year, with average temperatures ranging from 8°C to 28°C (Korir and Ngenoh, 2019). Like VDM, the Narok Country depends on rainfed agriculture. The land is utilized for horticulture crops including tomatoes, potatoes, cabbage, beans, onion and indigenous vegetables, as well as for crops like wheat, barley, maize, beans, sugarcane, Irish potatoes, pigeon peas, cowpeas, sweet potatoes, and cassava. Also, farmers raise chickens and dairy cows for food (MoALFC, 2021). Most farmers in Narok County lack the financial resources and extension services to support sustainable agricultural production, as well as basic agricultural supplies and modernised technology (Lawrence and Rotich, 2021) whilst many villagers practice subsistence farming. Climate change-related shocks and risks, such droughts and floods, are increasing in frequency, severity, and unpredictability in Narok County (Korir and Ngenoh 2019). Kenya possesses an installed capacity of 2.3 megawatts. Approximately 57% of the energy is derived from hydro power, 32% from thermal sources, while the remainder consists of geothermal and emergency thermal power. Solar photovoltaic and wind power contribute a modest 2% to the energy mix. Hydropower has constituted between 38% and 76% of the generation mix, influenced by inadequate rainfall. Thermal energy sources have compensated for these shortfalls, comprising 16-33% of the energy mix. Kenya currently has 2,990 MW of installed (grid-connected) electrical capacity. The two main sources of electricity supply are hydropower and fossil fuels (thermal). 838 MW of hydropower, 863 MW of geothermal power, 2% from biogas cogeneration, 437 MW of wind, and 173 MW of solar power make up this generation energy mix. By the end of 2021, 8.6 million Kenyan households—or more than 75% of the country's total population—were connected to the grid (Energy and Petroleum Statistics Report 2023/2024). According to Stats Kenya, the household electrification rate for Narok County was 19.9% at the year 2019. Table *1* indicates the electrification rate across the six regions in Narok County.

According to Lawrence and Rotich, (2021), agriculture, mainly agricultural farming and pastoralism, and tourism, particularly wildlife tourism associated with the Maasai Mara National Reserve, are the main drivers of Narok County's economy. The study further opines that traditional plant use is of tremendous importance in society and accelerating loss of traditional plant knowledge due to deforestation is of great concern.

Table 1: Electrification rates of Narok County as at 2019 (according to Stats Kenya – accessed 27 March 2025).

Region	Electrification rate (%)
Narok North	44
Narok East	23.9
Narok South	9.0
Narok West	6.6
Kilgoris	14.8
Emurua Dikirr	8.9

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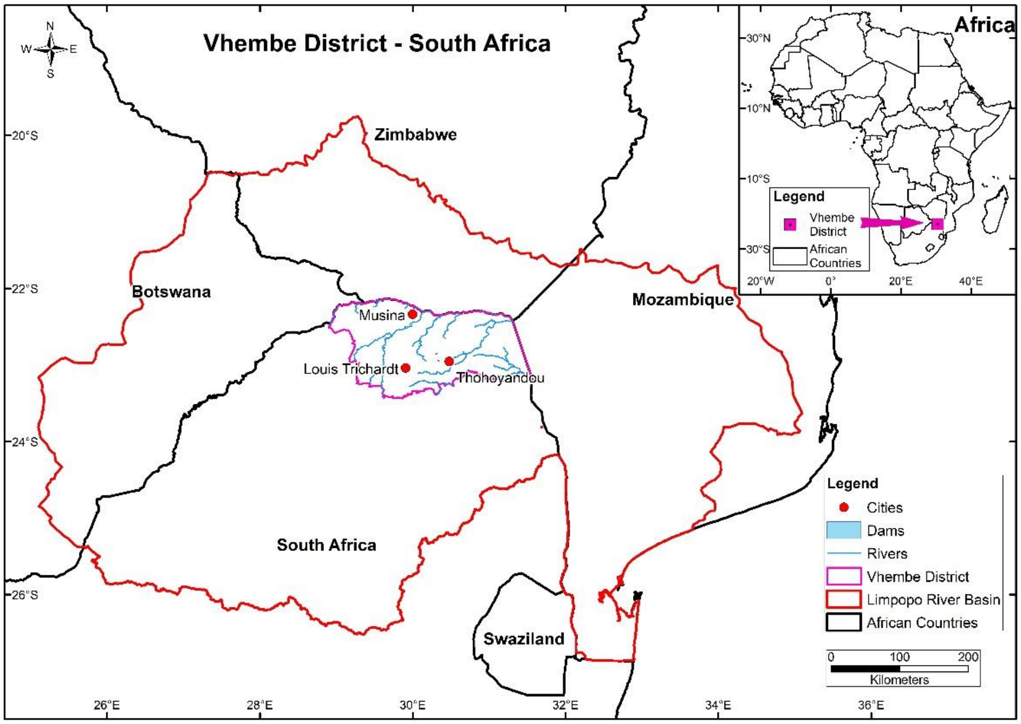

Figure 1*:* Vhembe District Municipality, South Africa.

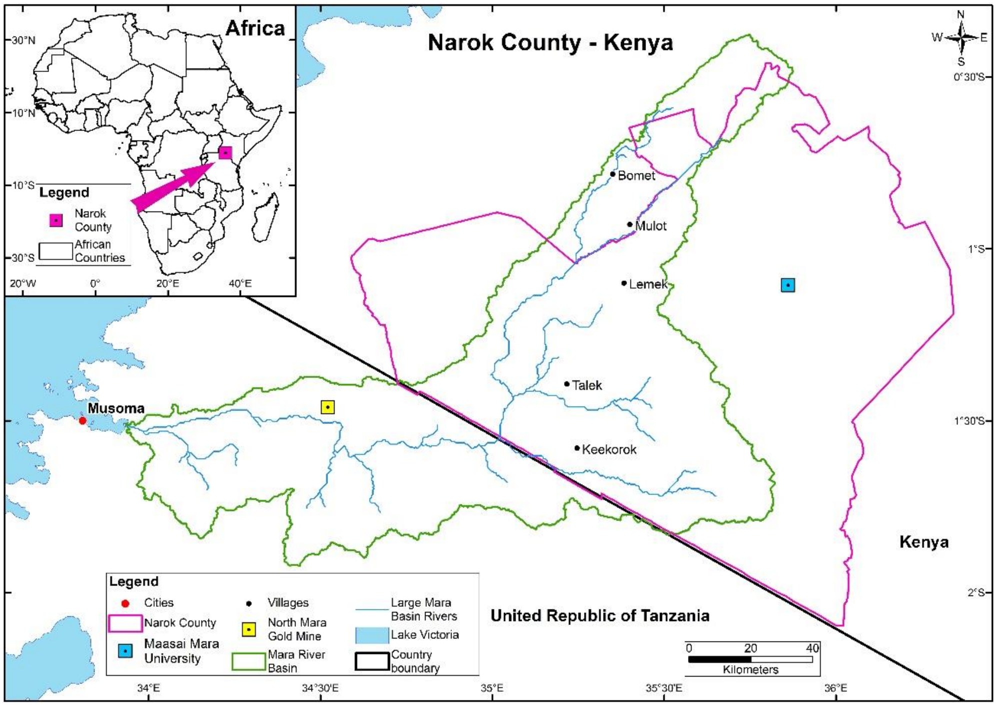

Figure 2: Narok County, Kenya.

2.2.2. Materials and Methods

2.2.2.1. Research Design

The present study was based on two qualitative methodologies which included a survey analysis and the desktop analysis study as shown in Figure 3. The current study used stratified random sampling where we considered communities in the villages, farmers, schoolteachers and local businesspeople (Figure 4). The analysis was predicated on qualitative mapping of the links between the water, food and energy systems using data collected from 218 questionnaires responses, focused group discussions and observation from the field visits of study areas. The same questionnaire (appended as Appendix A and B) was used for both individual interviews and focused group discussions.

In Kenya the South African Weather Service (SAWS) team collaborated with Kenya Water Institute (KEWI). To ensure that the participants understand the questions, the questionnaire was translated into a local language (Swahili). Figure 4 demonstrates a briefing session between SAWS and KEWI personnel, to ensure all members were well informed on how to conduct the survey using both the electronic form and printed hard copies, interpret the questions into Swahili and pair up teams for the site visits.

The questionnaire analysis focused on distribution statistics, including the Multiple Correspondence Analysis (MCA) and the Likert analysis which are based on R software. The MCA is a statistical technique used to analyse relationships between multiple categorical variables. Meanwhile the Likert analysis was used to measure opinions of participants, where participants selected the number on the scale [1 – strongly disagree, 2 – Disagree, 3 – Neither agree or disagree, 4 – Agree and 5 – Strongly agree] which described statements of sustainable livelihoods, health and wellbeing in the community.

Furthermore, we developed a sustainable WEF nexus matrix and established a systematic map of causal relationships to visualize the linkages of water, energy and food systems to understand their complex relationships and to promote sustainable resource management. This causal relationship is advanced using Structural Equation Modelling (SEM) framework as reported in Zwane et al., (2024). From both the literature and survey responses we defined various factors which act as both the drivers and affect the intricate WEF Nexus system.

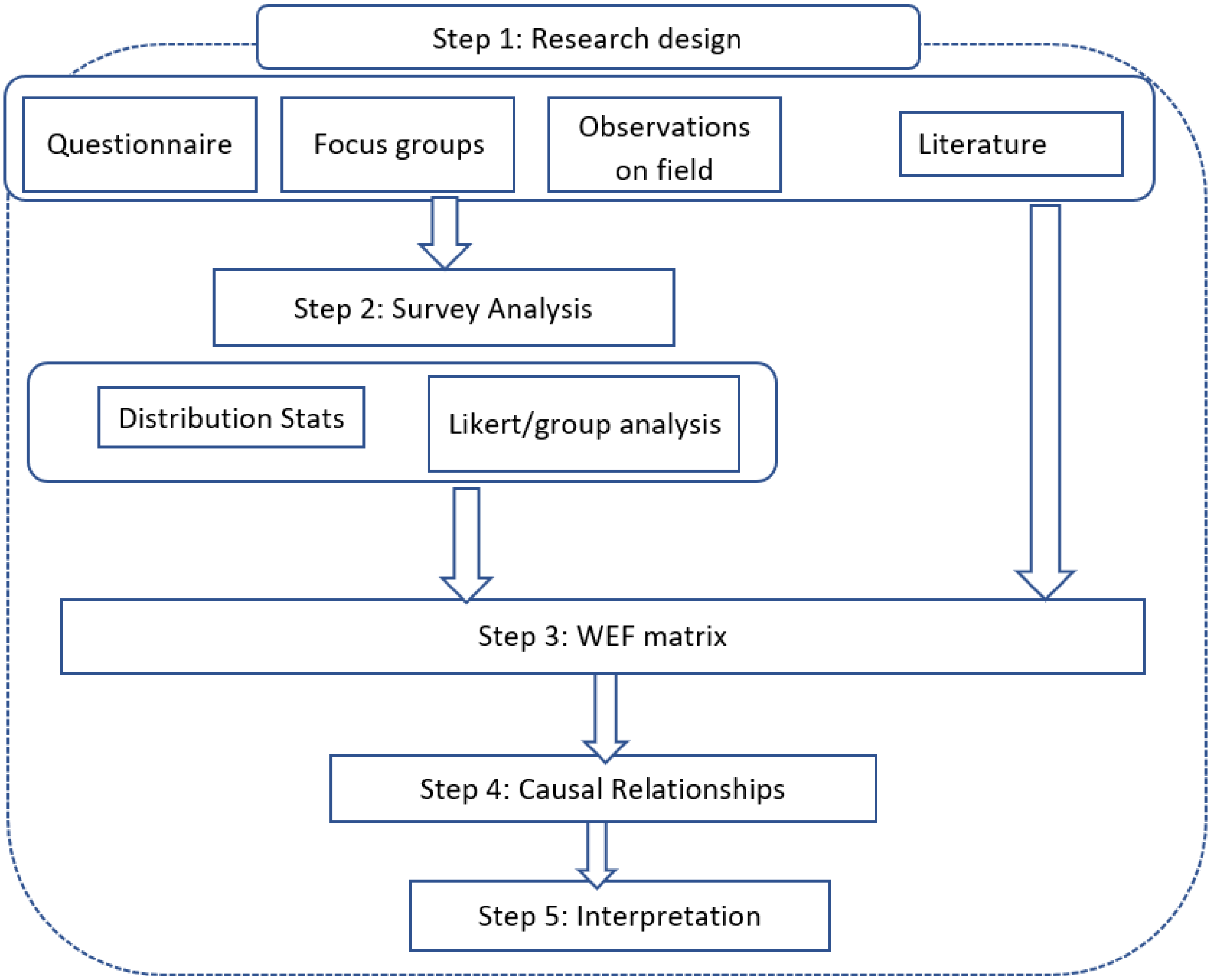

Figure 3: Methodology flowchart.

Figure 4: Brief meeting before field work between South African Weather Service and Kenya Water Institute.

2.2.2.2. Survey analysis and observations from the field

Using R studio (version 4.3.3, https://posit.co/products/open-source/rstudio/), the survey responses are analyzed for distribution statistics. Table *2* defines the variables considered for analysis from the questionnaire. We describe the survey elements in line with the short name. The categorical variables were computed using statistical packages on the open-source software RStudio and these were described as counts percentages at 95% confidence interval (CI). The Vensim PLE 9.3.5 x64 software (trial version - https://www.vensim.com) was employed for causal loop diagram for sustainable WEF resources. The causal loop diagram was utilized to map and comprehend a system's intricate, dynamic relationships and feedback loops in the study site in order to better identify possible issues, anticipate consequences, and improve decision-making. According to Terrapon-Pfaff et al (2018) not all complex systems such as the WEF nexus links can be described as linear relationships between the sectors. The interrelationships within and across systems can happen concurrently or progressively and they are frequently circular and dynamic. The above-mentioned analysis has allowed us to understand how each component of the WEF nexus influences each other.

Table 2: Questionnaire Elements.

Short name	Full name	Survey Elements
wef_dev	Development	Which illustrate that the community experiences scarcity of water, energy and food resources due to changes in population and urbanization,
Wef_cc	Climate Change	The community/region experiences scarcity of water, energy-food resources due changes in climate change hazards
vul	Vulnerability	The community/region is a high-risk area and is vulnerable to extreme weather due to economic, and socio-environmental drivers of change
exp	Exposure	The community has high exposure & is sensitive to the limited water, energy-food resources due to economic and socio-environmental drivers of change
wash	Water, Sanitation and Hygiene	The community experiences mortality rate that can be attributed to unsafe water, unsafe sanitation, and lack of hygiene
nutr	Nutrition	The malnutrition prevalent in the community is associated to the food insecurity among the residents
a_water	Access to water	Available & accessible freshwater resources in the community can meet our needs now & in future
u_water	Unsafe water	The community experiences mortality rate that can be attributed to unsafe water
c_rec	Recovery	Community is able to recover from economic and socio-environmental disruptions (e.g. famine, floods, high food prices, conflict)
p_gov	Government	The well-being of the community is impacted by weak government institutions
crop_irr	Crop irrigation	Crops produced through irrigation in the community can meet our needs now & in future
a-elec	Access to electricity	The electricity accessible to the community is enough to use now and, in the future,
ac_ecd	Economic development	Energy produced to support economic growth in the community is enough for our needs now and in future
s-food	Food security	Our access to nutritive and affordable food by the community can meet our needs now & in future

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The observations on the field are illustrated in Figure 5 and Figure 6. Shown in Figure 5 are some of the participants who were engaged in the study, participating in focus groups discussions as well as individual interviews. The participants included communities in the villages, farmers, schoolteachers and local businesspeople. Figure 6 illustrates some of the hydroclimatic extremes that were observed in Narok County where a makeshift bridge was constructed by community members to access the reserve in Lovengton Estate during the heavy rains that flood the road. Also evident in Figure 6 is a rainwater harvesting system used by households to collect water during dry seasons.

Figure 5: Participants engaged in individual interviews and focus group discussions.

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Figure 6: Hydroclimatic extremes observed on the field – makeshift bridge contracted by communities which is useful during flooding (left) and the rain harvesting system to collect water during dry seasons (right).

2.2.2.3. Desktop analysis study - Water-Energy-Food Resources Stature in Vhembe District and Narok County

The present study also considered relevant literature that was downloaded from commonly used Web of Science and Scopus databases. These included a wide range of document types, such as articles, reviews, conference papers and chapter books as shown in Table *3*.

Table 3: Summary of WEF Nexus documents analysed.

Document type	**Number of documents**
Article	27
Conference and proceeding papers	4
Book chapter	2
Book	2
review	10
Total	45

Vhembe District Municipality WEF Resources Stature

Table *4* summarizes the WEF resources available in the VDM. In general, rural areas of South Africa are vulnerable to water shortages, and the VDM is no exception, with limited access to reliable water resources and the communities rely on unclean open sources such as rivers and dams as well as groundwater resources (Vhembe District Municipality, 2012). According to Jaka (2019), the Limpopo Province has four water management catchment areas, namely, Limpopo, Olifants, Luvuvhu-Letaba, and Crocodile West Marico. The Luvuvhu-Letaba is the primary catchment for the Vhembe District Municipality. Other water resources include 12 dams, 3 weirs, and 38521 boreholes for access to groundwater (Jaka, 2019). The water supply that mainly comes from dams, rivers, and boreholes is inadequate as some dams are over-allocated or have no allocation for domestic use. Drying up groundwater sources and pollution have been reported in Masisi communities (Vhembe District Municipality, 2012). Additionally, the expansion of mining activities that use a large proportion of the water in the municipality further threatens water security. The Vhembe District Municipality suffers from poor water quality and drying up of groundwater, funding, maintenance, theft, and vandalism. Notably, the number of boreholes in the district seems high. However, they are unequally distributed across the municipal areas - Makhado has 23165, Thulamela 7871, Musina 1170, and Mutale 3057 (Jaka, 2019). The district thus has a relatively limited supply of both ground and surface water and is consequently stressed by the high demand for water for various activities, including agriculture, human consumption, and mining. Water management in the district faces the following challenges: an imbalance between the supply and demand for water, alien invasion, inappropriate land uses in the river valleys, the impact of fertilizers and pesticides, inadequate monitoring, poorly managed sewage systems, high concentrations of pit latrines, flood events and droughts.

The VDM is mandated to increase the accessibility of clean, efficient, and reliable energy for all. From a total of 296 000 households in the district, only 196 000 households have access to electricity. This is about 66% as per the official statsSA (2016) records and (Botai et al., 2024). The rest of the households rely on wood since it is cheaper than other sources. According to Jaka (2019), the choice of fuel in Vhembe is influenced by household income, with the preferred energy sources being electricity or gas. A survey conducted by StatsSA (2016) on energy sources and access indicated inequalities among the districts. It was established that Thulamela (32.79%) and Makhado (28.84%) local municipalities have a high number of people with access to electricity using prepaid. Meanwhile, Musina and Collins Chabane have the highest percentages of non-paying residents connected to other sources at 0.32% and 0.21% respectively. Also, Musina and Makhado have the highest proportion of connected and paying residents. Overall, the VDM showed diversity and inequality in electricity access. Feasibility studies conducted in the district indicated that the municipality has the potential for alternative energy in the form of biogas which can be used to meet the current energy needs of poor households.

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

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

Table 4: WEF resources available in the VDM.

Sector	WEF nexus resources	Reference
Water	Surface water (55.4%), groundwater (44.2%), missing system (0.4 %)	Nesamvuni et al., 2022
Energy	Wood (63%), electricity (34%), gas (2%), paraffin (1%)	Rasimphi and Tinarwo, 2020
Food	Vegetable garden (32%), crops (20.6%), poultry (11%), fishery (4.7%), piggery (3.2%), cattle (7.9%)	Oni et al., 2010

Narok County WEF Resources Stature

In Kenya, the selected study site is in Narok County in southwestern Kenya. Focusing on some parts of the Mau Forest Catchment Basin (MFCB), which includes the Mau Water Tower (also known as the Mau Forest or Mau Forest Complex). The Mau Water Tower, which is one of the five largest water towers in Kenya, supports agriculture, tourism, and hydro energy production (Odawa and Sewo, 2019). Table *5* summarizes the WEF resources available in Kenya. In terms of water supply, the catchment provides several main rivers with water, including the Mara River, Southern Ewaso Nyiro, Nzoia, Kerio, and Sondu Miriu, which flow into Lake Victoria, and some into Lake Natron and Nakuru. The quality and quantity of water in the Mau Forest Water tower has declined due to rapid population growth in the area resulting in land-use change and cover as well as loss of biodiversity as evidenced by a sharp increase in the area covered by grassland and severe decline in forest cover which enhances the water tower's ability to replenish springs and rivers (KWTA, 2015). The average temperatures range from a minimum of 8˚C to a maximum of 28˚C and the County has two rainy seasons with short rains averaging 500 mm, and long rains averaging 1800 mm per annum (Korir and Ngenoh, 2019).

Approximately 252,880 hectares of Narok County's land are used for crops like wheat, barley, maize, beans, sugarcane, Irish potatoes, finger millet, pigeon peas, cowpeas, sweet potatoes, and cassava, and horticultural crops like tomatoes, potatoes, cabbage, French beans, onions, and indigenous vegetables. Farmers also keep dairy cows and poultry for subsistence (MoALFC, 2021). The main activities thus include small- and large-scale farming such as livestock rearing, maize and sorghum production, tea plantations, and dairy farming. Most farmers in Narok County work without basic agricultural inputs or modernized technology and lack adequate financial and extension services to promote sustainable production (Lawrence and Rotich, 2021). In Narok County, climate change hazards such as droughts and floods are becoming more frequent, more severe, and less predictable (Korir and Ngenoh, 2019). Furthermore, the population of Narok increased from 299319 in 1979 to 850920 in 2009, and the catchment has been experiencing a decline in riparian vegetation, loss of soil, and clearing of forests to expand human settlements as well as conversion to cropland (Mohtar al., 2015; 25 Odawa and Seo, 2019). Additionally, the energy supply is mainly from hydro-power plants, the Sondu- Miriu hydro-power plant on the Sondu River, and the catchment, in general, is estimated to have the capacity to produce 40% of Kenya's current generation capacity (UNEP, 2015). Forests have also been cleared for firewood as a primary source of fuel for cooking and logging. Efforts are being made by government agencies to support the reforestation and delineation of extremely critical water catchments and biodiversity hotspots for conservation.

Table 5: WEF resources available in the Narok County.

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

2.3. RESPONSE SURVEY RESULTS

2.3.1. Questionnaire distribution statistics

Figure 7 demonstrates the correlation between variables and principal dimensions. Clearly shown is that most variables are correlated with dimension 1 at 9.92%. These variables have a positive correlation, such that a change in one influence the other. Only a few variables such as crop irrigation, access to water, access to electricity and economic development have less correlations with both dimensions. These variables are not influenced when other variables change.

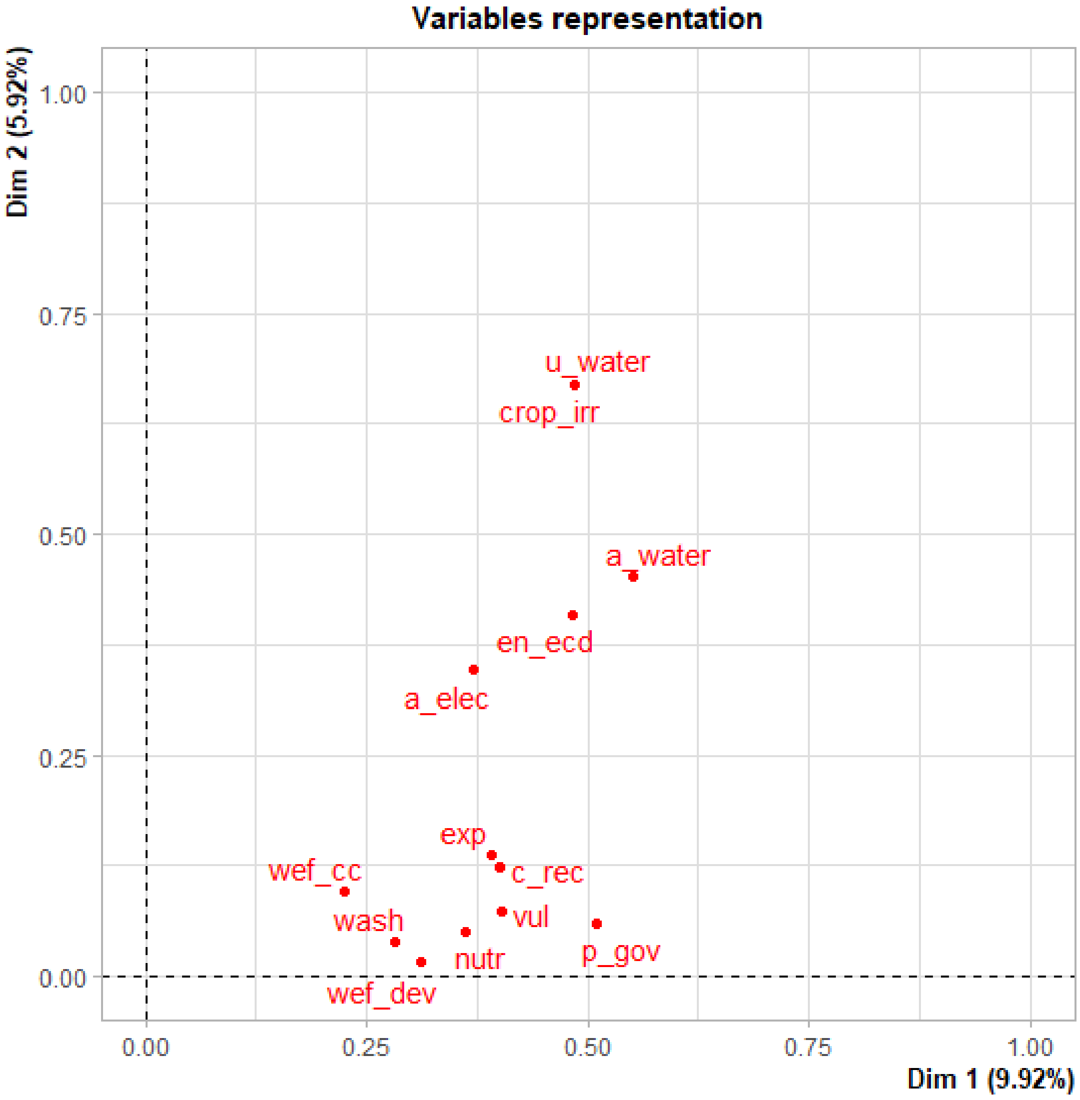

Figure 7: Multiple Correspondence Analysis (MCA) factor variables representation map.

The clustering process categorized the responses into 1 to 5 categories or clusters. Figure 8 shows the confidence ellipses around the categories of the selected variables for both study sites. Illustrated in this figure are the categories that are different from each other in the multidimensional space. The ellipse's size indicates the level of confidence in the estimate, such that the larger the ellipse means more uncertainty. On the other hand, when the ellipses overlap, means the corresponding categories may not be significantly different from each other. Responses from both the study sites indicate that the clustered variables do not significantly differ regarding how climate change impacts sustainable livelihoods, health and well-being in the communities. These included vulnerability, exposure, governance, climate change, water, sanitation and hygiene. This is depicted by the elliptical numbers given in Figure 8.

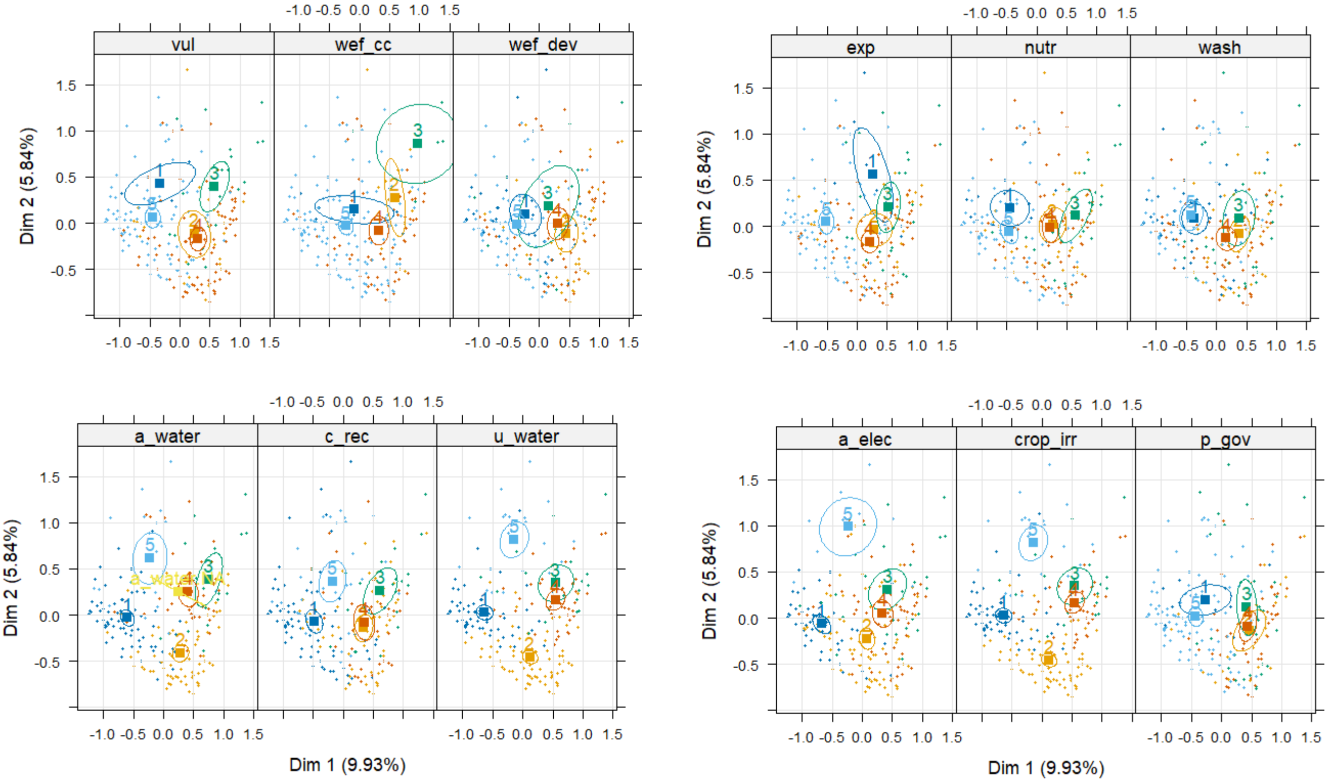

Figure 8: Multiple correspondence analysis performed using the plotellipses function in R, which draws confidence ellipses around the categories of all variables used for both Narok County and VDM.

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The distribution of responses from Narok County and VDM on the question “Does the community or region experience scarcity of water, energy, or food resources due to climate changes?” is shown in Figure 9. In Vhembe, 40% of respondents strongly agreed, and another 40% just agreed. A total of 15% were neutral, while only 5% disagreed. A substantial difference in the responses were observed for Narok County, where 63.3% strongly agreed and 26.3% agreed. About 1.3% were neutral, and 5.6% and 3.5% disagreed or strongly disagreed. The results in Figure 9 illustrate that communities in both the study areas agree that the regions have experienced a scarcity of WEF resources due to the changing climate.

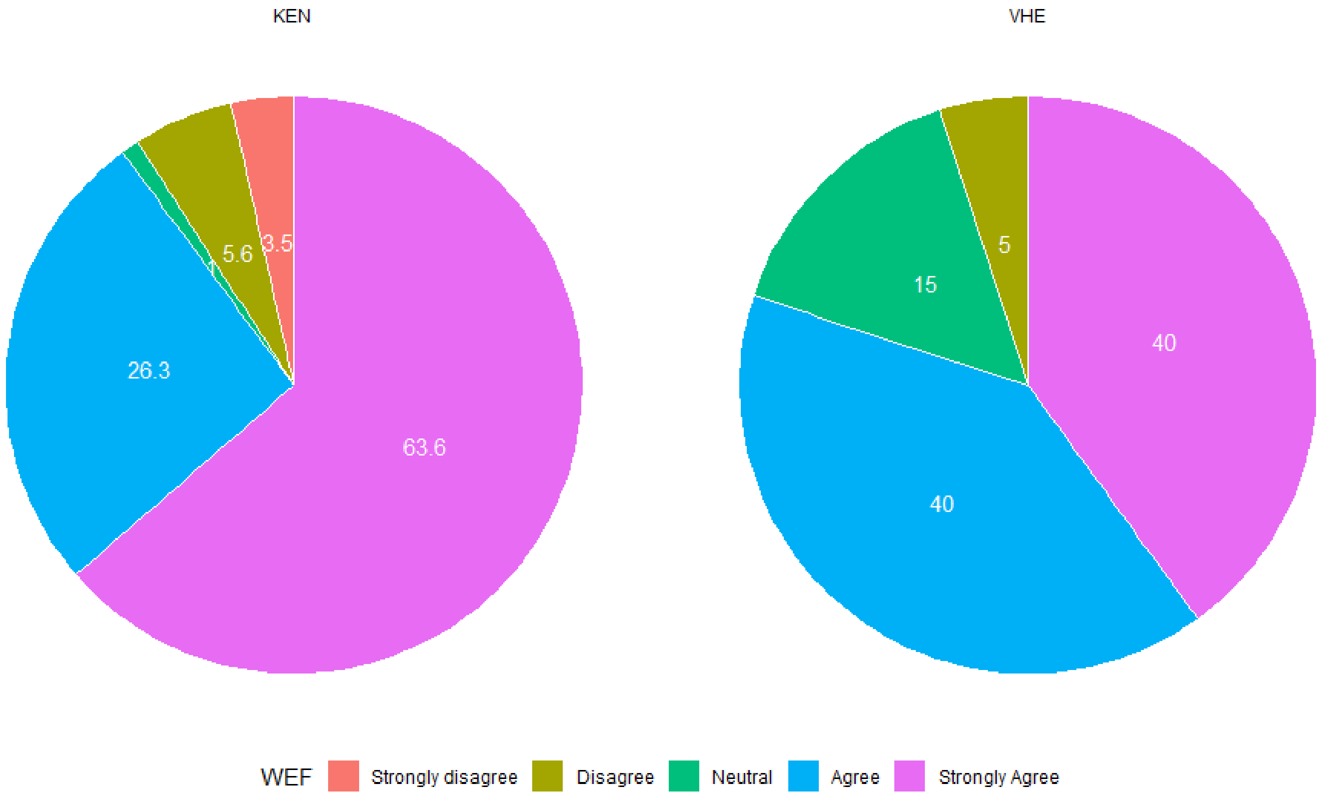

Figure 9: Distribution of responses (in percentages) per country Kenya (Narok) vs South Africa (Vhembe).

Figure 10 depicts the combined distribution of survey responses from Narok County and Vhembe District Municipality across all variables listed in Table *2* - which assesses sustainable livelihood, health and wellbeing in the communities. Demonstrated in Figure 10 is that the questionnaire was well structured. Most respondents had an opinion about the statements, and only a small percentage of respondents were neutral (grey). On the statements that looked at WEF resources,

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climate change, vulnerability, governance, exposure, nutrition, development, water – sanitation and hygiene, the respondents generally agreed/strongly agreed with a rating scale of 4/5, which is indicated by a percentage range of 58 – 90% (green). Meanwhile, statements that looked at WEF resources, recovery, access to electricity, access to water, crop irrigation, economic development and food security, the respondent generally strongly disagreed/disagreed with a rating scale of 1/2 indicated by a 63 – 71% range (brown).

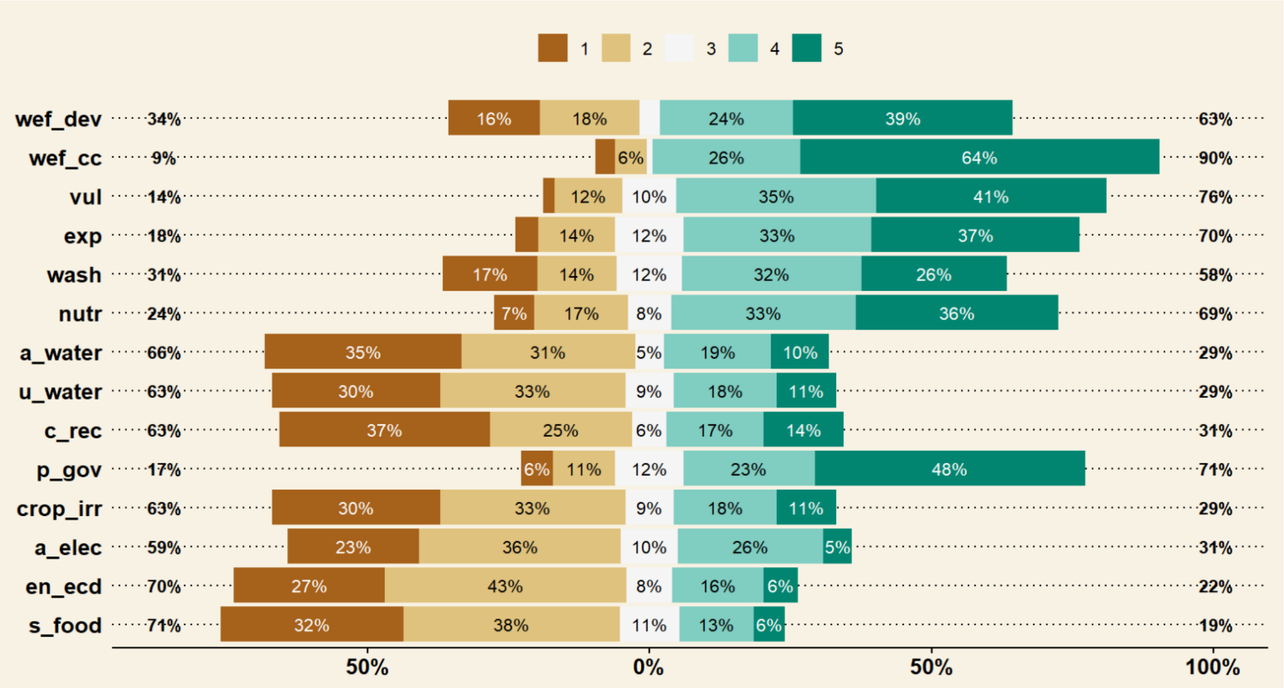
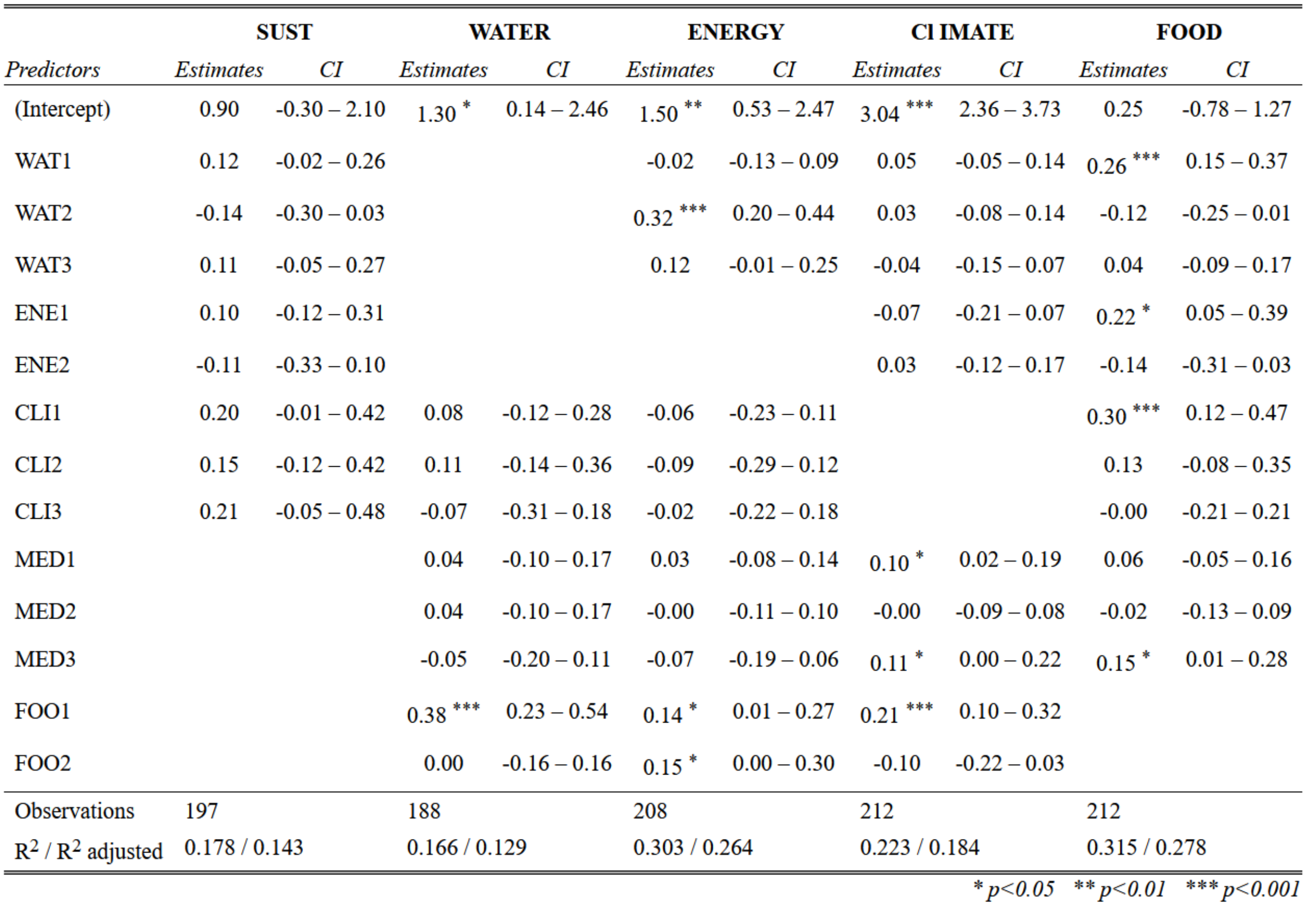


Figure 10: Combined Distribution of responses (%) from Kenya (Narok) and South Africa (Vhembe).

2.3.2. Multi-regression analysis of the constructs

Table *6* shows the results for the multi-regression analysis for the combined constructs to explain why using linear models is not feasible for complex interrelationships. As shown in Table *6*, while the constructs and independent variables show dispersed statistically significant linear correlations, the individual constructs have statistically significant linear correlations (i.e., the *p*-values were all <0.1). Across the five constructs in Table 6, we demonstrated that the relevance varies between 18% to 32% (see the r^2 and r^2 adjusted).

Table 6: Descriptive analysis for multi-regression analysis for combined constructs.



	SUST		WATER		ENERGY		Cl IMATE		FOOD	
Predictors	*Estimates*	*CI*	*Estimates*	*CI*	*Estimates*	*CI*	*Estimates*	*CI*	*Estimates*	*CI*
(Intercept)	0.90	-0.30 – 2.10	1.30^{*}	0.14 – 2.46	1.50^{**}	0.53 – 2.47	3.04^{***}	2.36 – 3.73	0.25	-0.78 – 1.27
WAT1	0.12	-0.02 – 0.26			-0.02	-0.13 – 0.09	0.05	-0.05 – 0.14	0.26^{***}	0.15 – 0.37
WAT2	-0.14	-0.30 – 0.03			0.32^{***}	0.20 – 0.44	0.03	-0.08 – 0.14	-0.12	-0.25 – 0.01
WAT3	0.11	-0.05 – 0.27			0.12	-0.01 – 0.25	-0.04	-0.15 – 0.07	0.04	-0.09 – 0.17
ENE1	0.10	-0.12 – 0.31					-0.07	-0.21 – 0.07	0.22^{*}	0.05 – 0.39
ENE2	-0.11	-0.33 – 0.10					0.03	-0.12 – 0.17	-0.14	-0.31 – 0.03
CLI1	0.20	-0.01 – 0.42	0.08	-0.12 – 0.28	-0.06	-0.23 – 0.11			0.30^{***}	0.12 – 0.47
CLI2	0.15	-0.12 – 0.42	0.11	-0.14 – 0.36	-0.09	-0.29 – 0.12			0.13	-0.08 – 0.35
CLI3	0.21	-0.05 – 0.48	-0.07	-0.31 – 0.18	-0.02	-0.22 – 0.18			-0.00	-0.21 – 0.21
MED1			0.04	-0.10 – 0.17	0.03	-0.08 – 0.14	0.10^{*}	0.02 – 0.19	0.06	-0.05 – 0.16
MED2			0.04	-0.10 – 0.17	-0.00	-0.11 – 0.10	-0.00	-0.09 – 0.08	-0.02	-0.13 – 0.09
MED3			-0.05	-0.20 – 0.11	-0.07	-0.19 – 0.06	0.11^{*}	0.00 – 0.22	0.15^{*}	0.01 – 0.28
FOO1			0.38^{***}	0.23 – 0.54	0.14^{*}	0.01 – 0.27	0.21^{***}	0.10 – 0.32		
FOO2			0.00	-0.16 – 0.16	0.15^{*}	0.00 – 0.30	-0.10	-0.22 – 0.03		
Observations	197		188		208		212		212	
R^2 / R^2 adjusted	0.178 / 0.143		0.166 / 0.129		0.303 / 0.264		0.223 / 0.184		0.315 / 0.278	

* *p<0.05* ** *p<0.01* *** *p<0.001*

2.3.4. Sustainable WEF resources interdependence in the study sites

Table *7* demonstrates the connection between sustainable WEF resources and their interdependencies in VDM and Narok County. Water is needed to produce energy, while energy is needed to collect, distribute and treat water. On the other hand, both energy and water are required to produce food. The energy created can be utilized as an input in both the water and agricultural systems to provide clean drinking water, to preserve, process or prepare agricultural and food.

Furthermore, the systematic map in Figure 11 displays the various factors that act as both drivers and effects in the intricate WEF nexus system. These results illustrate that the use of energy in the agriculture sector primarily reinforces positive trends leading to increased agricultural production, processing and food conservation resulting in greater food security. Similarly, it is

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observed when energy is an input variable for the water system. The amount of irrigated land and the supply of clean water can both be increased by using energy generated to run irrigation pumps or provide clean water for people. Overall, observed from the systematic map, it is challenging to guarantee the availability and security of all three resources in the study sites due to the increased demand for water, food and energy. This inherent increase in resource competition is a result of population growth. The WEF nexus components security features can be compared to the difference between supply and demand.

Table 7: Sustainable WEF nexus matrix.

	Energy access	Water access	Food access
Energy	• Energy for lighting and electrical appliances	• Water for electricity generation • Water used for electricity can change water flow and have a negative impact on the environment. • Water used for electricity can reduce water availability for other uses.	• Energy for lighting and electrical appliances • Bioenergy generation using feedstock
Water	• Energy is used to clean dirty water (i.e., boiling/filter) • Energy used for irrigation and efficient irrigation technology save energy.	• Efficient irrigation technology save energy	• Use of biomass waste for energy reduces water pollution. • Food processing • Water for sanitation and irrigation

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	• Water pumps increase water availability.		
Food	• Reduce greenhouse gases by reducing the use of wood and charcoal. • Agricultural processing (use of solar stoves/biogas)	• Improved irrigation can boost agricultural production. • Water pollution due to crop production	• Use of water and water pollution can be decreased by sustainable agricultural practices

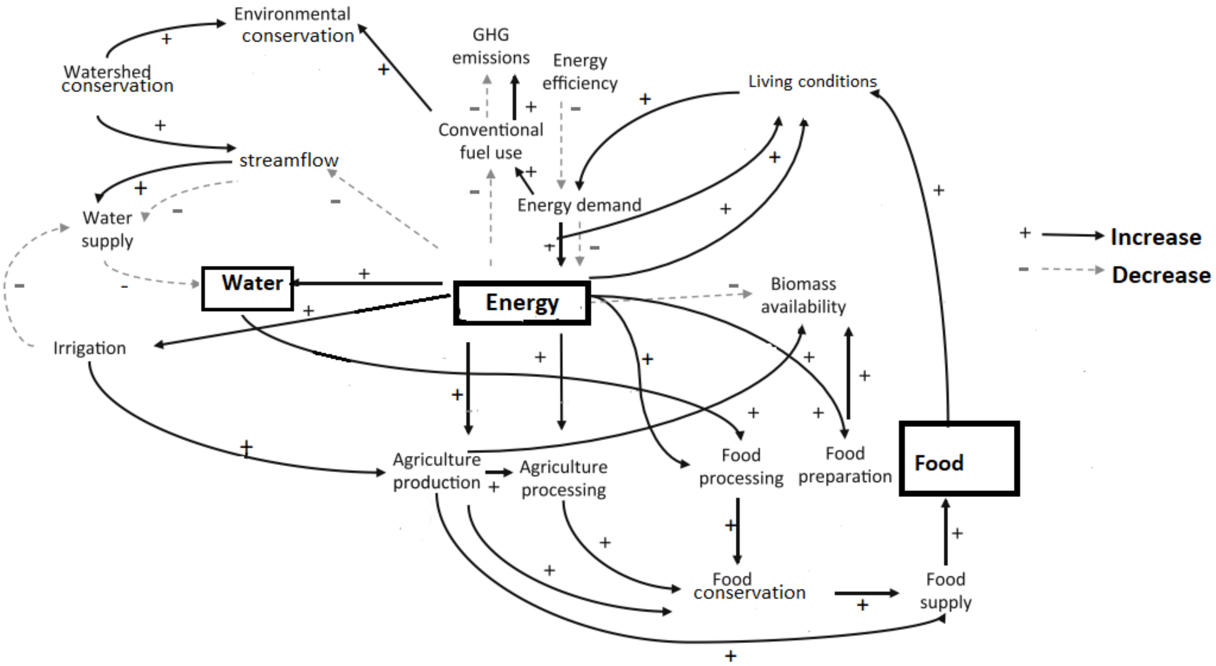

Figure 11: Systematic map of causal WEF relationship in Narok County and VDM.

2.4. DISCUSSION AND CONCLUSION

The analysis in this study showed that most variables correlate with dimension 1 at 9.92%. Moreover, responses from both the study sites indicated that categories of the selected variables are different from each other, illustrating that climate change impacts the variables differently. The study demonstrated that the communities in both study sites agree that the regions have experienced scarcity in WEF resources due to climate change. Overall, the questionnaire was well structured as most respondents had an opinion about the statements and only a small percentage of respondents were neutral. The findings make it clear that there is an imbalance in resource management in the Vhembe District Municipality and Narok County. These results corroborate the findings in a study by Botai et al (2024) which assessed rural livelihoods, health and wellbeing with the WEF nexus framework in Narok County and VDM, where the findings highlighted that the resources for sustainable livelihoods in VDM are more sustainable than those in Narok County. Moreover, the study by Botai et al (2024) also classified both study sites under the lowly sustainable category as indicated by the composite index of 0.143.

In this chapter we evaluated the interdependencies of WEF nexus resources in Narok County, Kenya, and Vhembe District Municipality, South Africa to support the endeavor of better planning and management of the three important economic sectors (Water, Energy and Agriculture). To reduce environmental risks and socioeconomic trade-offs, it is imperative that effective policies be developed to maximize WEF resources and support sustainable management. On the other hand, to meet the sustainable development goals, these interventions, which are meant to guarantee fair access and effective use of WEF resources should be customized to the local context and capacity to promote and maintain the well-being of marginalized populations and livelihood outcomes. In the current assessment we determined that the communities in the study sites rely on water resources that are not metered. The food security systems also rely on non-irrigated systems (rainfall). Moreover, over 50% of the energy resource is non-gridded electricity. As a result, the water, energy and food nexus are comparable in both study sites. Hence our approach to assess the interdependences is plausible. The current and future climate scenario in both study sites is aligned, suggesting that developmental options constrained by the WEF nexus resources require a conceptual framework that addresses the gaps and opportunities characteristic of the two study sites. It is against this background that authorities or policymakers in the study sites ought to embrace the clarion call of the new initiative of early warning for all as championed by the United Nations Secretary General. The findings in this chapter necessitate the development of suitable policies and tactics that will implement and reinforce the community-level interconnections of the WEF resources. Furthermore, for informing policy formulation that guides interventions in line with balancing socio-economic and socio-ecological systems.

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CHAPTER THREE: THE LINKAGES BETWEEN SUSTAINABILITY AND THE WEF RESOURCES BASED ON STRUCTURAL EQUATION MODELLING FRAMEWORK UNDER CHANGING CLIMATE: A CASE STUDY OF NAROK COUNTY (KENYA) AND VHEMBE DISTRICT MUNICIPALITY (SOUTH AFRICA)

The primary goal of this chapter is to investigate potential synergy between driving variables and WEF resources using structural equation modeling (SEM) technique to explain the explicit or implicit consequences of climate change on WEF resources in the study sites. This study is anchored on the null hypothesis (H0), whereby no interdependencies exist between the state of the climate and WEF resources, as constrained by sustainable development options. The results show that the proposed hypothesis does not hold, but rather, an alternative hypothesis (Ha)−there exist linkages between climate change and WEF resources−holds (Zwane et al., 2024). Food has a direct positive impact on climate and sustainability, while both water and energy have an indirect negative impact. Moreover, the climate construct indicated a significant direct link to sustainability for all the relationships explored (Zwane et al., 2024).

3.1. INTRODUCTION

Global major concerns, including climate change, environmental degradation, migration, population increase, and fast urbanization, require integrated approaches to effectively manage resources and guarantee sustainable accessibility and availability (Mabhaudi et al., 2019). According to Nhamo et al (2020), integrated solutions call for stakeholder buy-in and public awareness from the onset as they require a paradigm change from the typical “silo” approach to a cross-cutting one that recognizes and encourages cross-sectoral convergence and coherence in resource management. The nexus of water, energy and food (referred to as the WEF nexus) is increasingly being recognized as a strategy to efficiently manage sustainable development due to the current and anticipated growth in global demand and pressure on WEF resources, as well as the strong links between the WEF sectors and sustainable development (Nhamo et al., 2018).

The WEF nexus is intricate yet critical in resolving many of the problems humanity faces (Botai et al., 2021). The WEF nexus is three-dimensional: 1) utilized as a conceptual framework, 2) as an analytical tool, and 3) as a discourse. A study by Nhamo et al (2020), suggested that the conceptual framework makes it easier to understand how WEF connections support coherence in policymaking and advance sustainable development. Meanwhile, as an analytical tool, it systematically applies quantitative and qualitative methods to understand the interactions among WEF resources. Lastly, as a discourse, it is a tool for problem-framing and fostering cross-sectoral collaboration.

Many African countries still have significant disparities in demand and accessibility, implying that millions of people lack water, energy, and food resources (Rasul et al., 2016). The three resources are strongly linked, and any impact on one affects the other. A WEF nexus approach could unlock the positive synergies required to prompt regional socio-economic development. The necessity for a coordinated and integrated approach to sustainable development, like the WEF nexus model, is further justified by climate change estimates showing greater demand for water, energy, and food resources (Bhaduri et al., 2015 and Zaman et al., 2017). An improved, integrated management of the WEF sectors has the potential to substantially improve climate resilience at local, national and regional levels (Thuo et al., 2017).

According to Thuo et al (2017), Kenya foresees becoming a “middle-income country providing a high quality of life to its citizens by 2030”. The Kenya Vision 2030 also included the WEF sectors. For energy, Kenya wants to produce more energy at a cheaper cost and consume it more efficiently. The government is committed to institutional reforms, including increasing the number of independent power producers and exploiting new sources, including geothermal, coal, and renewable energy sources. In terms of agriculture, Kenya aims to increase revenues in agriculture, livestock, and fishing by adding value to the products before they are sold. This involves using 1.2 million hectares of newly opened land and 1 million hectares of existing uncultivated land. Lastly, vision 2030 recognizes that Kenya is a water-scarce country and suggests building two large dams and 22 medium-sized dams and renovating a few irrigation projects. In Narok County, livelihoods and WEF resources are threatened by climate change. Rural households in Narok depend on various activities and income bases, and crop and livestock production are prominent (Thuo et al., 2017).

Similar restrictions apply to South Africa’s WEF resources. Literature shows that access to water, energy, and food is crucial for securing fundamental human rights and dignity and is central to global sustainability challenges, making it necessary to manage and allocate the available resources sustainably and integrated (Mabhaudhi et al., 2019 and Nhamo et al., 2020). In Vhembe District Municipality (VDM), the community relies on dirty open water reservoirs like rivers and dams due to a lack of reliable water resources. The district’s water security is also in jeopardy due to the rise of mining operations, which consume significant water. According to Botai et al

(2024), about 66% of households in VDM have access to electricity while the rest rely on wood and other affordable energy resources. Rain-fed agriculture is the primary source of income in households that are engaged in agriculture (Kom et al., 2020, Botai et al., 2024).

The present study seeks to apply structural equation modelling (SEM) methodology to explain the explicit or implicit impacts of climate change on WEF resources in Narok County (Kenya), and Vhembe District Municipality (South Africa), with the main aim being to explore synergies between WEF resources and driving factors. Moreover, the intent of the study is to distinguish the direct and indirect effects of WEF security. Additionally, the specific objectives of the study include, a) enumerate the existing WEF resources in the study sites., b) conceptualise a structural equation model to mimic the interlinkages between climate change drivers and the WEF resources, and c) propose a scientific and practical contribution of the WEF nexus research paradigm from the perspective of SEM. The study sites are defined as rural with low economic activity, and the population depends on natural resources, mainly rainfed agriculture. The contemporary megatrends in society, in conjunction with shifts in the environment, technology, economy, politics and demographics, continue to strain the limited and diminishing natural resources, endangering their sustainability and, in turn, weakening the resilience of communities. According to Hair Jr et al (2021), the main core set of first-generation multivariate data analysis statistical methods used by researchers to empirically test hypothesized relationships between variables are the multiple regression, logistic regression and analysis of variance. These techniques are only applicable when measured variables contain neither systematic nor random errors. The SEM is regarded as the second-generation technique which enables researchers to simultaneously model and estimate complex relationships among multiple dependent and independent variables. In estimating the relationships, the SEM accounts for measurement error in observed variables. Consequently, the approach yields a more accurate measurement of the theoretical concepts (Hair Jr et al., 2021). It is important to note that SEM framework has not been used climate and WEF nexus research. To the best of my knowledge, this is the first time that this novel framework is considered in present research.

3.2. MATERIALS AND METHODS

The analysis in this study is based on qualitative mapping of the interlinkages between water, energy and food systems using data collected from questionnaires, focused group discussions and observations from the field when we visited the study areas. In this study we also considered relevant literature that was downloaded from Web of Science and Scopus. Using R studio, the survey responses were analyzed for distribution and descriptive statistics. The SEM utilized is a statistical framework used to analyse relationships between multiple variables. The SEM combines factor analysis and multiple regression to analyze complex relationships between latent and observed variables. The SEM consists of the measurement model and the structural model where the measurement model defines how the latent variables are measured by the observed variables where: -

1) $x = \Lambda x\ \xi + \delta$ and $y = \Lambda y \eta + \epsilon$ (Hair Jr et al., 2021)

- x and y are vectors of observed variables
- ξ and η are latent variables
- Λx and Λy factor matrices
- δ and ϵ represent measured errors

The structural models indicate the relationships between latent variables using: -

2) $\eta = B\eta + \Gamma\xi + \zeta$ (Hair Jr et al., 2021)

- B represents the matrix of coefficients (regression paths) among endogenous latent variables
- Γ represents the effects of exogenous latent variables on endogenous latent variables
- ζ represents the residual errors in structural relationships

Equation 1 and 2 allow SEM to model the measurements of abstract concepts and the directional influence among them. In the present study, the “Independent variables” is water, energy and food. Meanwhile, the “Dependent variables" is climate change and sustainability. We formulated three relationships defined as below: -

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- Relationship 1 – Water – Energy – Climate – Sustainability (WECS) with the paths water, energy to climate and sustainability.
- Relationship 2 – Water – Food – Climate – Sustainability (WFCS) with the paths water, food to climate and sustainability.
- Relationship 3 – Energy – Food – Climate – Sustainability (EFCS) with the paths energy, food and climate and sustainability.

In the present study, the survey responses were examined for distribution and descriptive statistics, where the student-t test was used to compare the mean between responses of the two study sites. The Bartlett test was also used to test equal variances in Kenya and South Africa responses. In this regard, if $p \leq 0.05$, the Chi-Square test is considered significant, then the null hypothesis is rejected, and consequently, the variances are assumed to be unequal. Furthermore, we considered the multi-regression analysis, in which we investigated the data from the two sites against the independent variables.

A WEF matrix was formulated from both literature and survey responses, which informed sustainable WEF resource interdependence in the study sites. Moreover, we defined various factors that act as drivers and affect the intricate WEF nexus system using the SEM. For the SEM, a partial least squares path model (PLS-SEM) was employed. The SEM focuses on the indirect (mediated) and direct effects of variables on other variables; the reliability analysis was conducted to validate the interrelationships between the constructs.

Two hypotheses were formulated as indicated below:

1) Null Hypothesis (H0) – No interdependencies exist between the state of climate and the WEF resources.
2) Alternative Hypothesis (Ha) – Interdependencies exist between the state of climate and WEF resources.

The (PLS-SEM) is used to visually display the hypotheses and the variable relationships that are analysed when SEM is applied. In the present analysis the “construct” also referred to as latent variables are represented in the path model as Hexagon. The indicators are the directly measured variables that contain raw data, i.e. for Water (WAT1 and WAT2), Energy (ENE1 and ENE2), Food (FOO1 and FOO2), Climate (CLI1, CLI2 and CLI3) and for sustainability (MED1 and MED2). The relationship between constructs as well as among constructs and indicators are depicted as arrows. The arrows are always single headed, thus pointing to directional relationships. The output values are represented by the β (for latent variables) and γ (measured variables). According to Hair Jr et al (2021) and Ullman and Bentler (2013), single headed arrows are considered predictive relationships and with strong theoretical support can be interpreted as causal relationships.

In this study, the analysed PLS-SEM for (Relationship 1, Relationship 2 and Relationship 3) were also subjected to a bootstrapped model. Bootstrapping is where you resample the data with replacement to create many simulated samples. The bootstrapped samples are used to estimate the variability, bias, confidence interval or performance of a model. In our analysis we calculated a 5% confidence interval for the mediated path (water-energy-food-climate-sustainability) and a 5% confidence interval for the direct path (climate-sustainability). The bootstrapped model output also shows the significant and non-significant levels within the relationships.

Furthermore, to validate the interrelationships between the constructs we utilized the reliability plot using the *psych* package in R Studio. According to Ullman and Bentler (2013), reliability refers to how well the observed variables (indicators) reflect the underlying latent variables they are supposed to measure. There are three key reliability metrics commonly assessed (see Table *8*): these are the Cronbach’s Alpha (α), Composite Reliability (ρC), and Dijkstra–Henseler’s rho (ρA). In the reliability graph we demonstrate the model confidence and validate the model accuracy, where Alpha, rhoC, and rhoA should exceed a threshold of 0.7. Cronbach’s Alpha evaluates internal consistency but assumes equal indicator loadings, making it less flexible. Composite Reliability (ρC) provides a more accurate estimate by accounting for varying indicator loadings, while rhoA offers the most robust reliability estimate, especially in PLS-SEM. When all three values meet or exceed 0.70, the construct is considered to have good reliability.

Table 8**:** Interpretation of reliability.

Metric	Meaning	Threshold	Interpretation
Alpha	Internal consistency	≥ 0.70	Overly strict
rhoC	True-score reliability	≥ 0.70	More accurate in SEM
rhoA	Reliability of construct	≥ 0.70	Most robust for PLS-SEM

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Figure 12 shows the hypothesized model where water, energy and food are the constructs, the independent variable is climate change, and the dependent variable is sustainability. Table 2 in chapter 2 defines the variables considered for analysis from the questionnaire.

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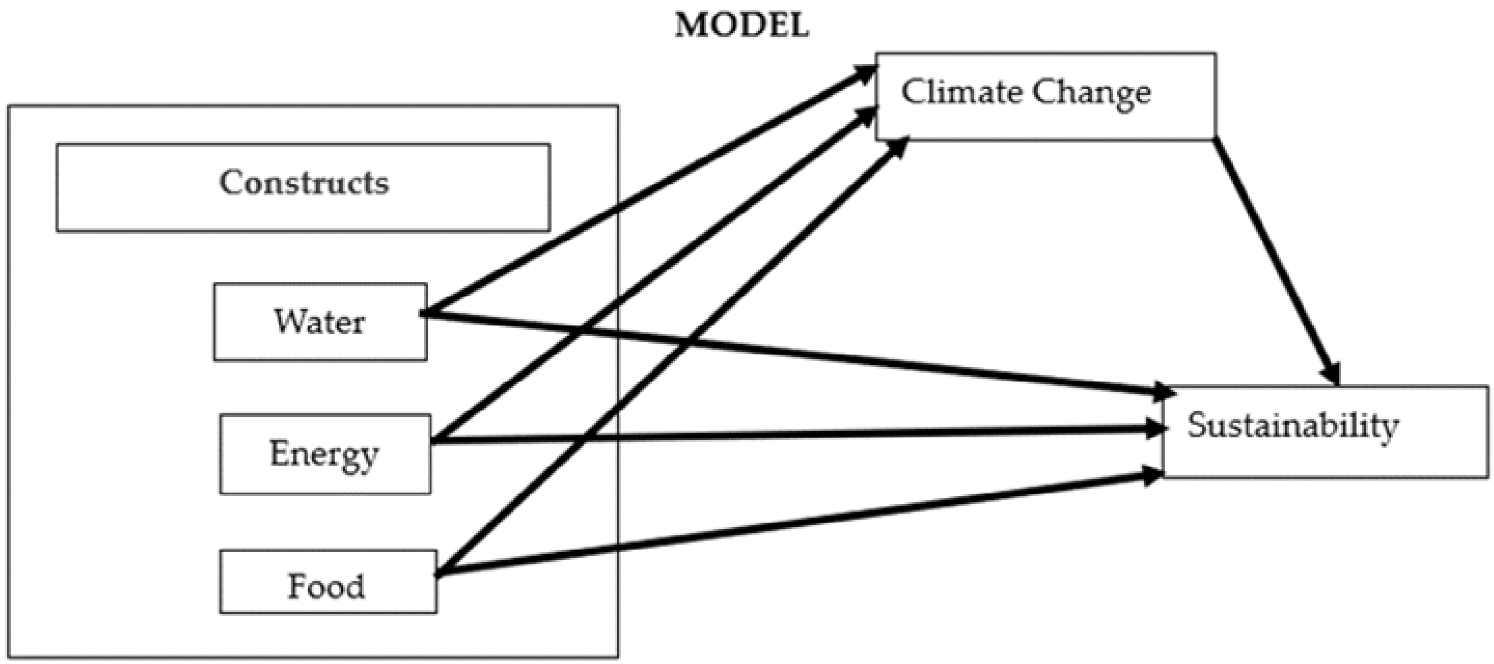

Figure 12: Hypothesized Structural Equation Model.

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3.3. RESULTS

3.3.1. Questionnaire descriptive statistics

Table *9* shows the descriptive statistics for the *t*-test and the Bartlet test in Narok County and Vhembe District Municipality and the results for the combined data for the two study sites. The student *t*-test and the Bartlet test showed that the *p*-values are less than 0.05, therefore significant with a 95% confidence interval that the alternative hypothesis is true: - There exist interdependencies between the state of climate and WEF resources.

Table 9: Descriptive statistics for the t-test and Bartlet test.

Options	t-test	Bartlet test
Narok	p-value < 0.00	p-value = 0.00
Vhembe	p-value < 0.00	p-value = 0.50
Combined	p-value < 0.00	p-value = 0.00

Table *10* illustrates the multi-regression analysis where three models involving contrast variables defined as climate change, sustainable development and community recovery were tested against the independent variables with significance exposure and nutrition. For Narok County, the model shows significant variations within the data, with p-values less than 0.05. The opposite is observed for the Vhembe District Municipality, where the model shows variation but is not statistically significant. The combined data for both the study sites gives a clearer picture, showing that the contrast and independent variables are statistically significant for all model variations with p-values < 0.05 and higher adjusted r-squared values. Therefore, we can reject the null hypothesis. This means that the alternative hypothesis is true: Interdependencies exist between the state of climate and WEF resources.

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Table 10: Descriptive analysis for multi-regression analysis.

Options	Contrasts	Independent variable with significance	P-value	Adjusted r squared
Narok	Climate Change	Exposure Nutrition	0.00	0.25
	Sustainable Development		0.000	0.16
	Community Recovery		0.020	0.06
Vhembe	Climate Change	Exposure Nutrition	0.13	0.46
	Sustainable Development		0.68	-0.14
	Community Recovery		0.32	0.22
Combined	Climate Change	Exposure Nutrition	0.00	0.26
	Sustainable Development		0.00	0.15
	Community Recovery		0.01	0.08

3.3.2. Structural Equation Model

Figure 13 – 18, Figure 19 – 24 and Figure 25 – 30 show the graphical illustrations of the three relationships formulated and investigated using SEM for Narok County, Vhembe District Municipality (VDM) and for both sites combined respectively. Relationship 1 comprises Water, Energy, Climate and Sustainability. Relationship 2 is Water, Food, Climate and Sustainability, and lastly, Relationship 3 is Food, Energy, Climate and Sustainability. In these Figures the output of the original model vs the bootstrapped model and a reliability graph are shown.

For the bootstrapped model, we calculated a 5% confidence interval for the mediated path (i.e. water-energy-food-climate-sustainability) and a 5% confidence interval for the direct path (i.e. climate-sustainability), indicated in Table 11 – 13. The bootstrapped model output also indicates the significant and non-significant levels within the relationships. Water, energy, food and

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sustainability have two measured observed variables, while climate has three. In addition, from the reliability graph, we show confidence and validate model accuracy, where Alpha, rhoC and rhoA should exceed a threshold of 0.7.

3.3.2.1. Narok County

Figure 13 demonstrates relationship 1, where both energy and water have an indirect effect on climate. The negative impact for energy is significant with a coefficient of β = - 0.16* (asterisk is the significance level), meanwhile the negative impact for water is insignificant. A direct insignificant effect is observed from energy to sustainability, and an indirect insignificant effect is observed from water to sustainability. Moreover, a significant positive impact from climate to sustainability is evident with a coefficient of β = 0.452***. In relationship 1, energy and climate show more reliability demonstrated in Figure 14.

Relationship 2 – water, food, climate and sustainability are demonstrated in Figure 15 . Food has a significant positive direct impact on both climate and sustainability. The significant level is more from food to climate than from food to sustainability, indicated by the coefficient of β = 0.414*** and β = 0.157* respectively. Similarly to relationship 1, climate is also directly linked to sustainability. Contrary to food, water indicates an indirect link to climate and sustainability with a coefficient of β = - 0.04 and a coefficient of β = - 0. 069, respectively. Climate construct shows more reliability in this model, and food is the least reliable, as illustrated in Figure 16.

Lastly, relationship 3 is explored in Figure 17, where food is directly linked to climate and sustainability with the significant coefficients of β = 0.401*** and coefficients of β = 0.168** respectively. In contrast, energy has an indirect negative impact on both climate and sustainability. The negative impact is significant from energy to climate with the coefficients of β = - 0.11*. Climate significantly affects sustainability with a positive impact factor coefficient β = 0.39 ***. The reliability graph shows that both energy and climate are reliable (Figure 18).

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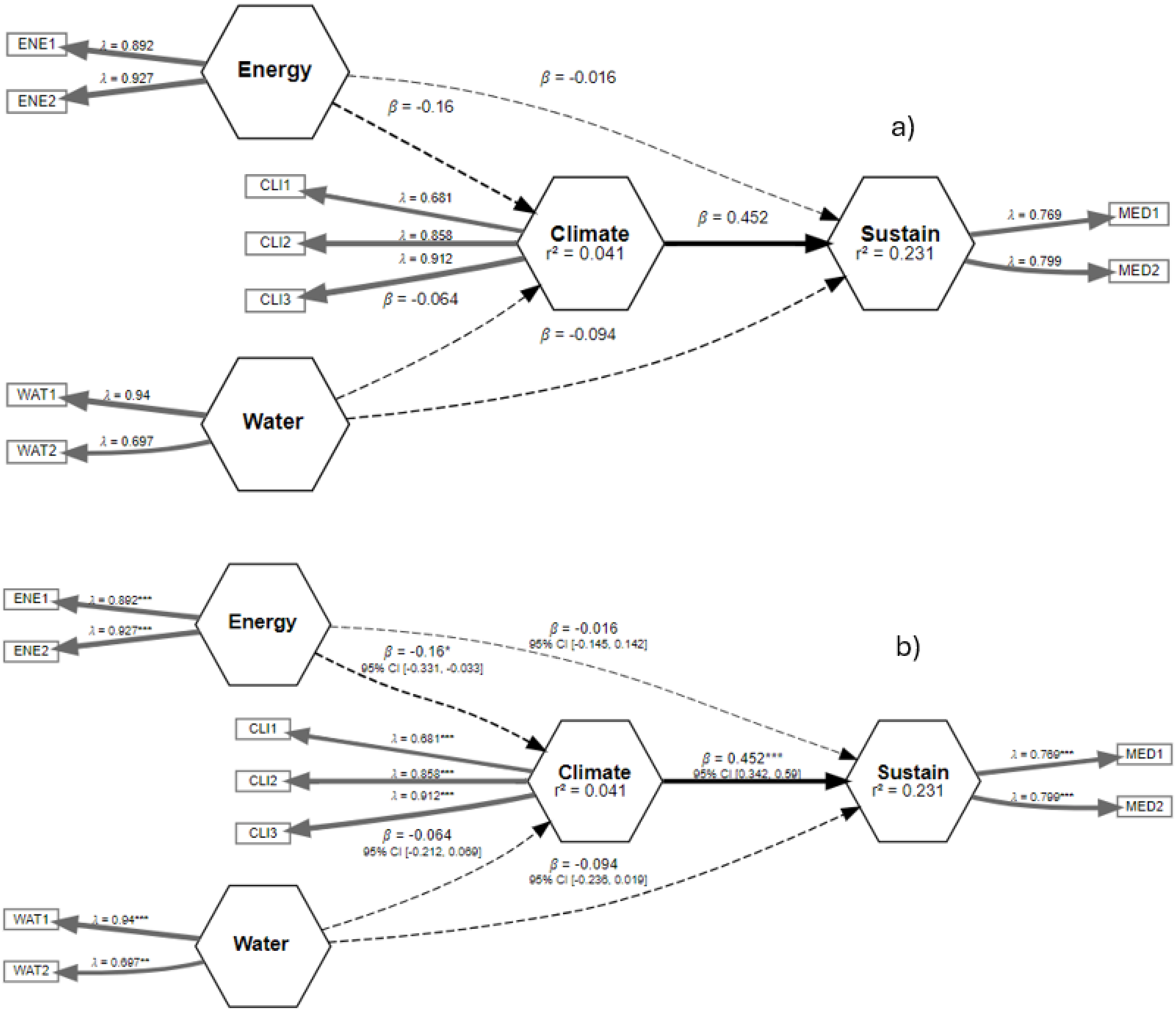

Figure 13: Relationship 1 for Narok County - water, energy climate and sustainability model a) and the bootstrapped model b). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

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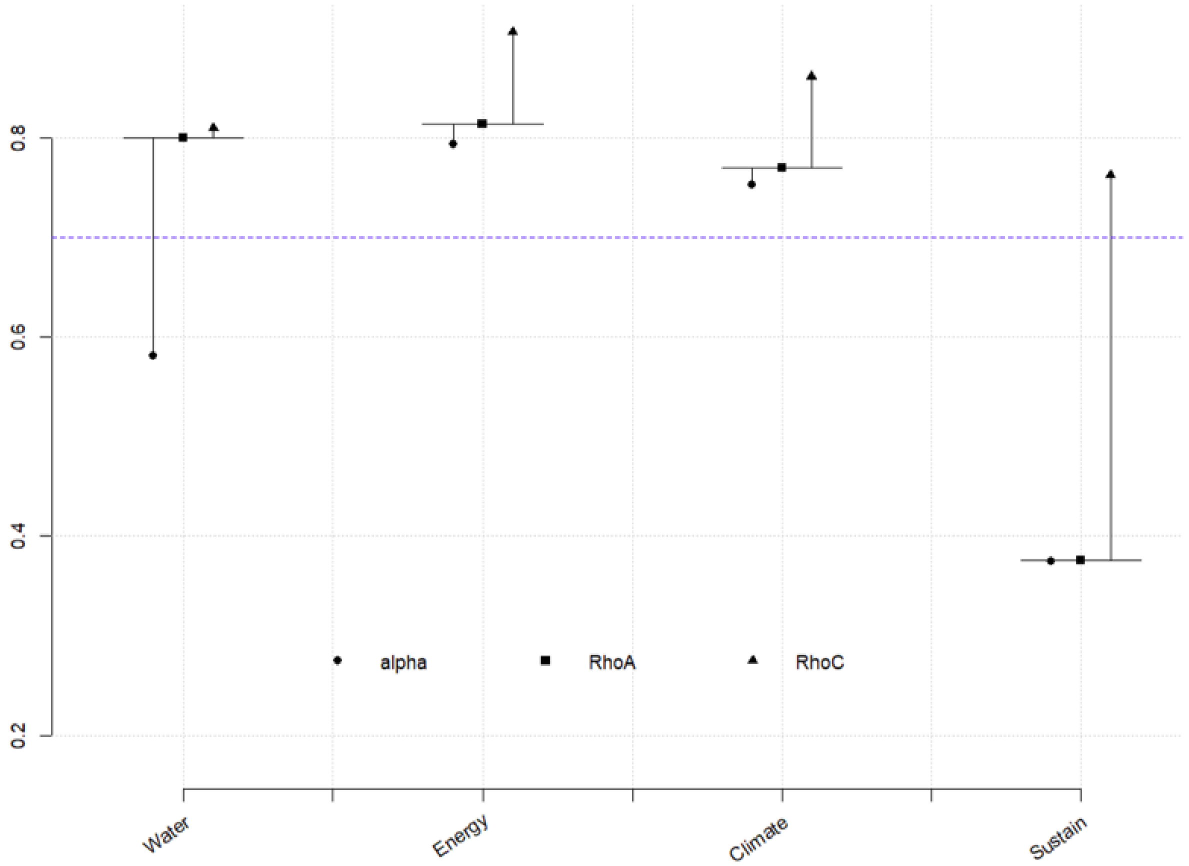

Figure 14: Reliability graph for relationship 1 – Narok County (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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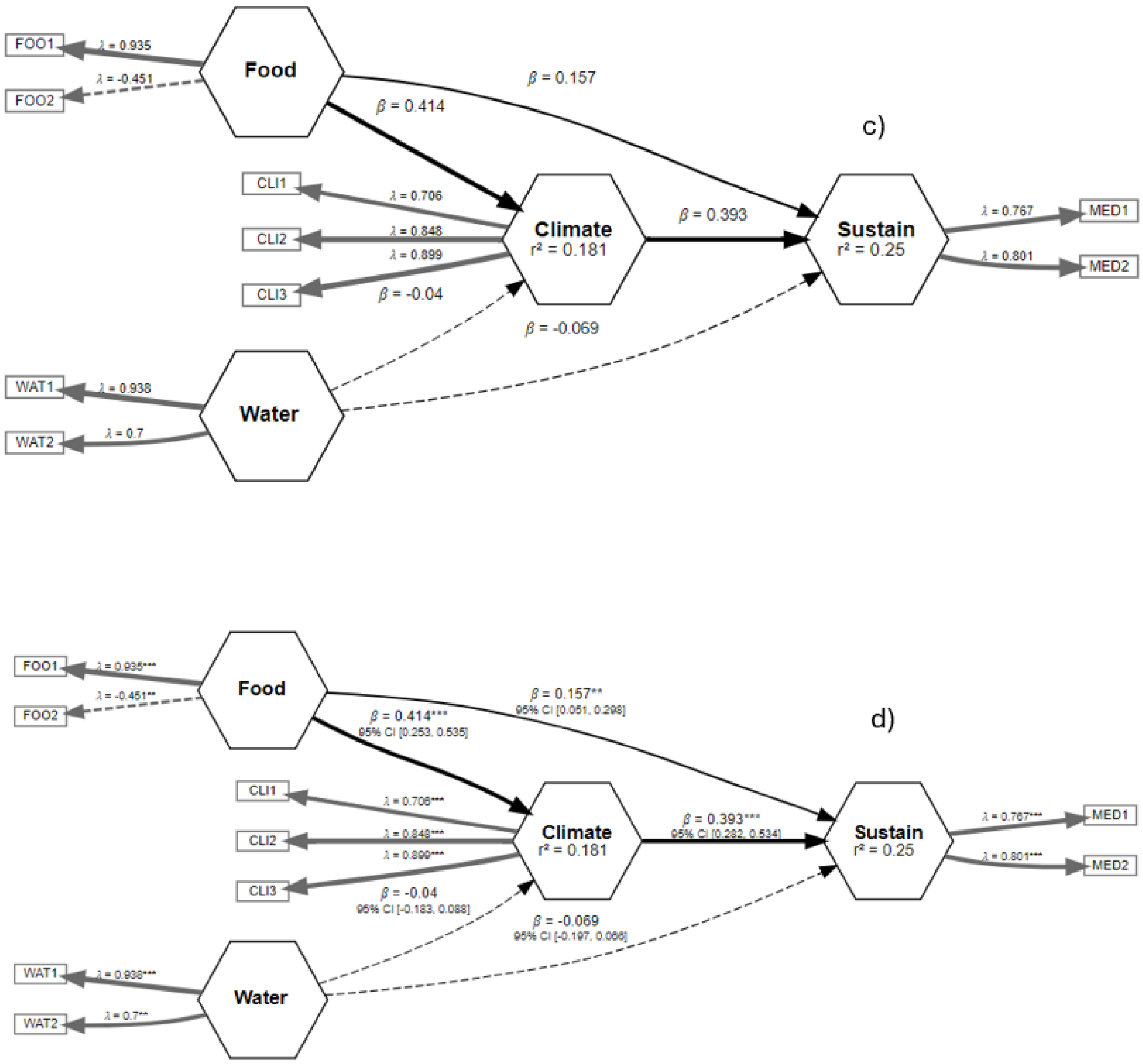

Figure 15: Relationship 2 for Narok County - water, food climate and sustainability model c) and the bootstrapped model d). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

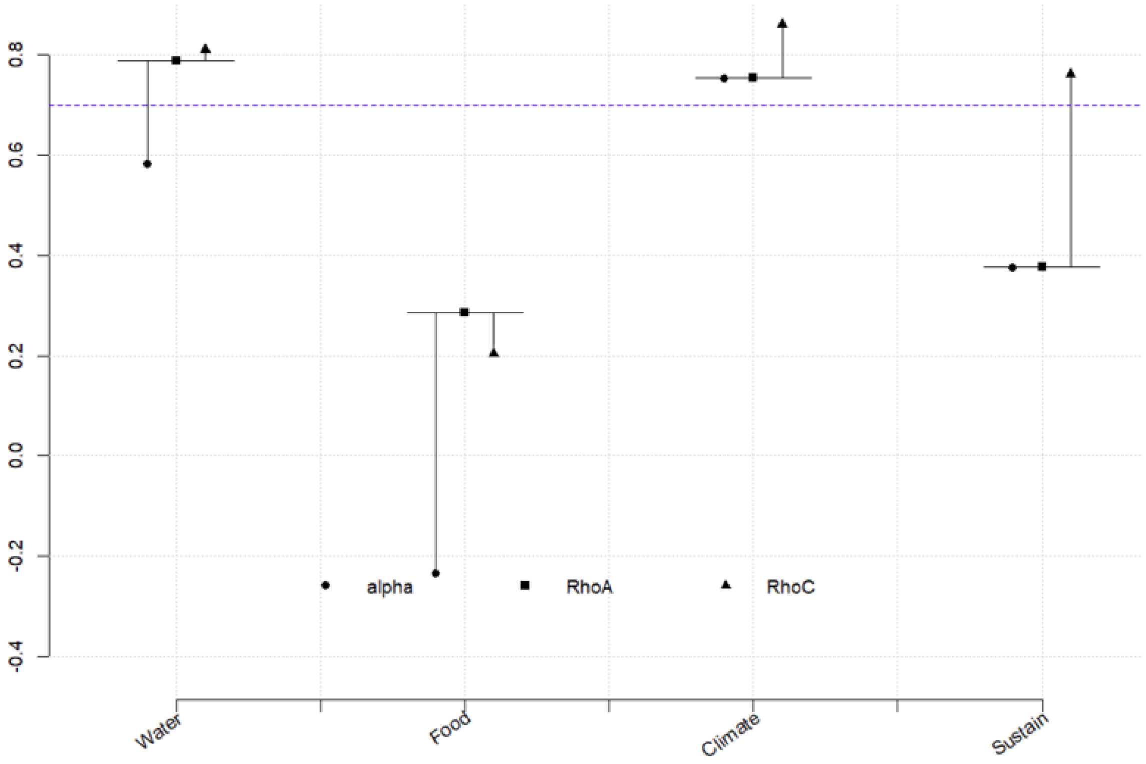

Figure 16: Reliability graph for relationship 2 – Narok County (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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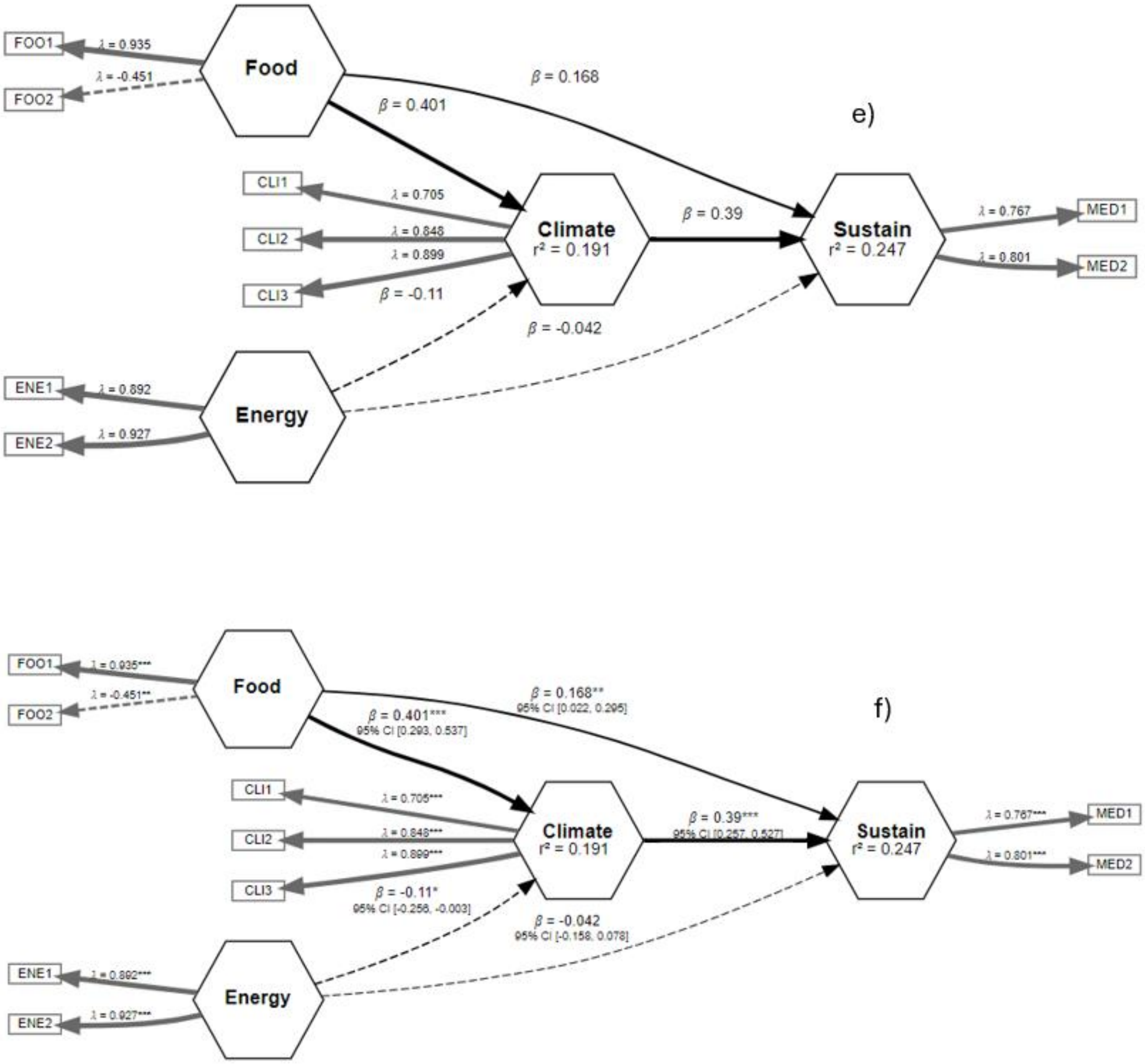

Figure 17: Relationship 3 for Narok County - Energy, food climate and sustainability model e) and the bootstrapped model f). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

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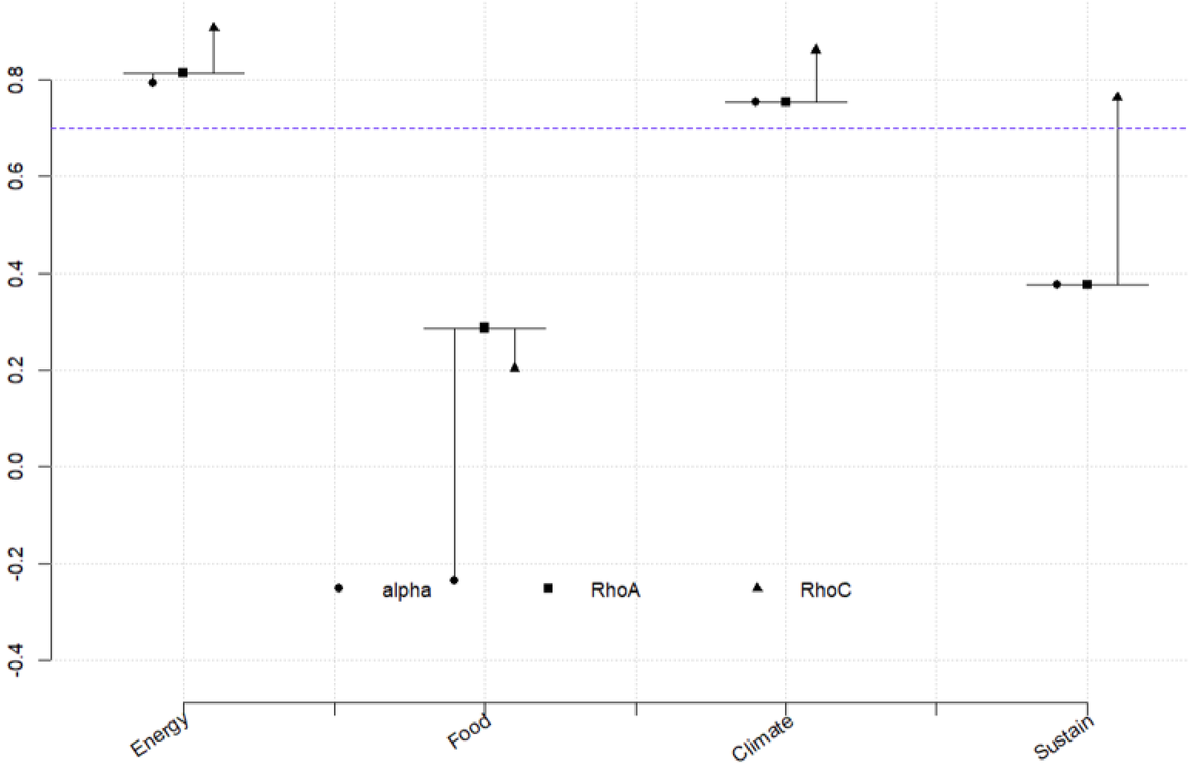

Figure 18: Reliability graph for relationship 3 – Narok County (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

Table 11: 5% confidence interval for mediated path for Narok County.

Mediation paths	Water, Energy, Climate and Sustainability			Water, Food, Climate and Sustainability			Energy, Food, Climate and Sustainability		
	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)
Water-climate-sustainability	0.03	-0.11	0.03	0.03	-0.07	0.04	-	-	-
Energy-climate-sustainability	0.03	-0.16	-0.02	-	-	-	0.03	-0.10	-0.00
Food-climate-sustainability	-	-	-	0.04	0.09	0.25	0.04	0.10	0.24
Climate-sustainability	0.07	0.34	0.59	0.06	0.28	0.53	0.07	0.26	0.53

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3.3.2.2. Vhembe District Municipality (VDM)

Relationship 1 is shown in Figure 19, where water and energy both indirectly affect climate. Both water (β = - 0.321) and energy (β = - 0.305) have a negligible negative impact. Also observed in this relationship is a direct insignificant effect from water to sustainability as well as a direct insignificant effect from energy to sustainability. Moreover, a considerable significant impact from climate to sustainability is visible with a value of β = 0.738*. Figure 20 illustrates the greater reliability found in relationship 1 between water and climate.

Figure 21 illustrates Relationship 2: water, food, climate, and sustainability. In this relationship Food directly and insignificantly impacts sustainability. Moreover, food has an insignificant indirect impact on climate. Like relationship 1, there is a clear correlation between climate and sustainability. Similarly to food, water has an indirect correlation with climate, while a direct link is observed with sustainability (β = - 0.346 and β = 0. 616, respectively). Figure 22 illustrates that the model indicates that water and climate are the most reliable, while food is the least reliable with Alpha, RhoA and RhoC below the threshold of 0.7.

In Figure 23, Relationship 3 is finally examined. It shows a direct link between food and sustainability and an indirect link between food and climate. The impact of food on climate and sustainability is insignificant. On the other hand, energy has a strong significant direct impact on sustainability (β = 0.595**) and indirectly impact on climate. Moreover, sustainability is impacted by climate, with a positive impact factor coefficient of β = 0.675*. Climate and energy are both dependable, according to the reliability graph in Figure 24.

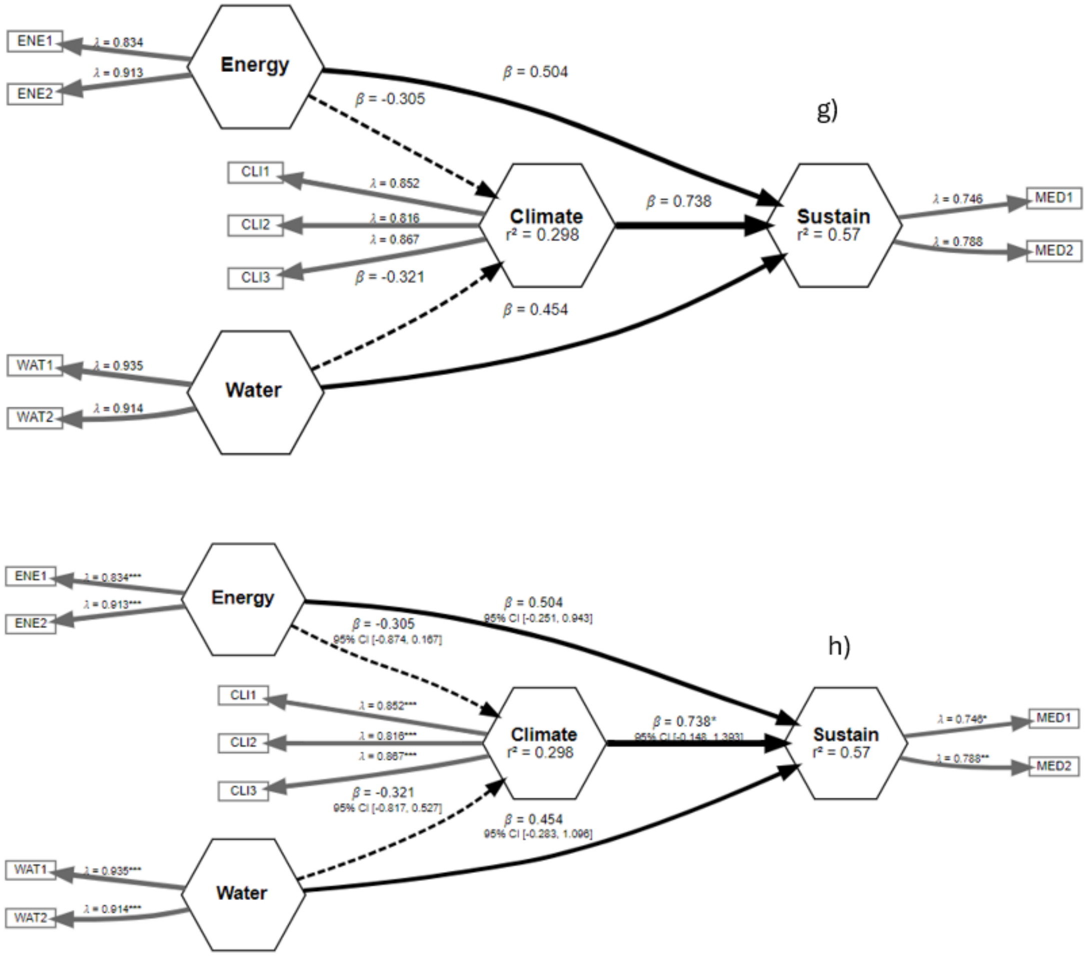

Figure 19: Relationship 1 for Vhembe District Municipality - water, energy climate and sustainability model g) and the bootstrapped model h). Asterisk is the significance level. * p < 0.05 ** p < 0.01 *** p < 0.001.

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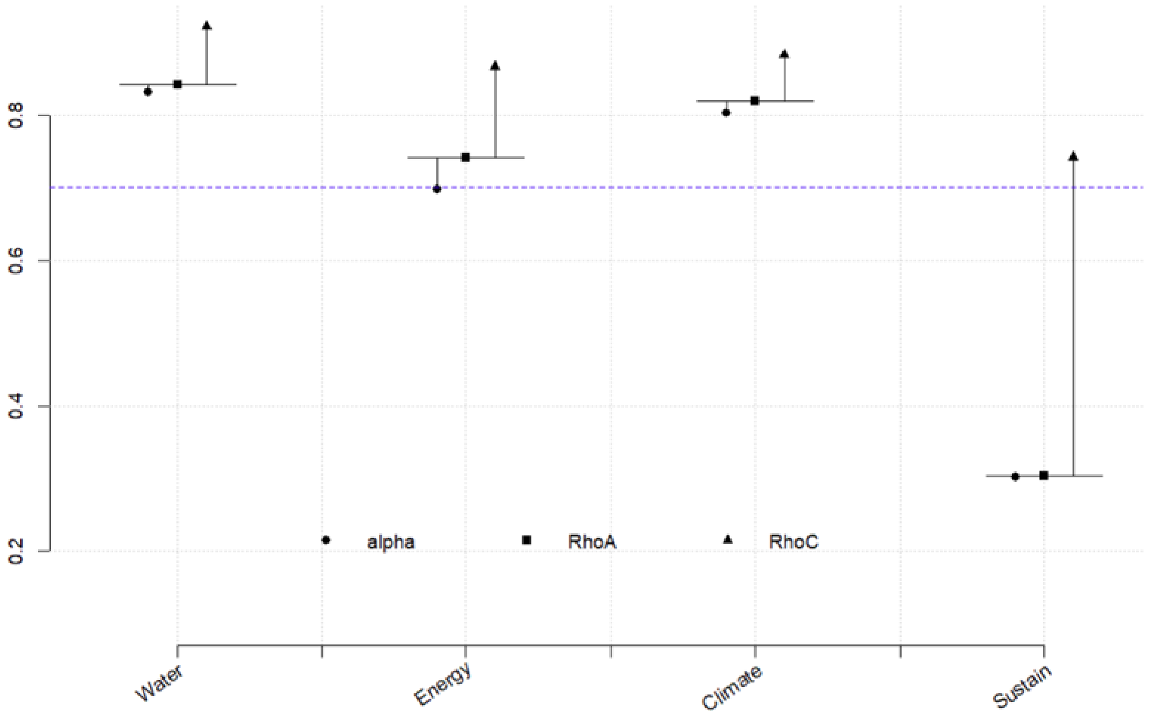

Figure 20: Reliability graph for relationship 1 – Vhembe District Municipality (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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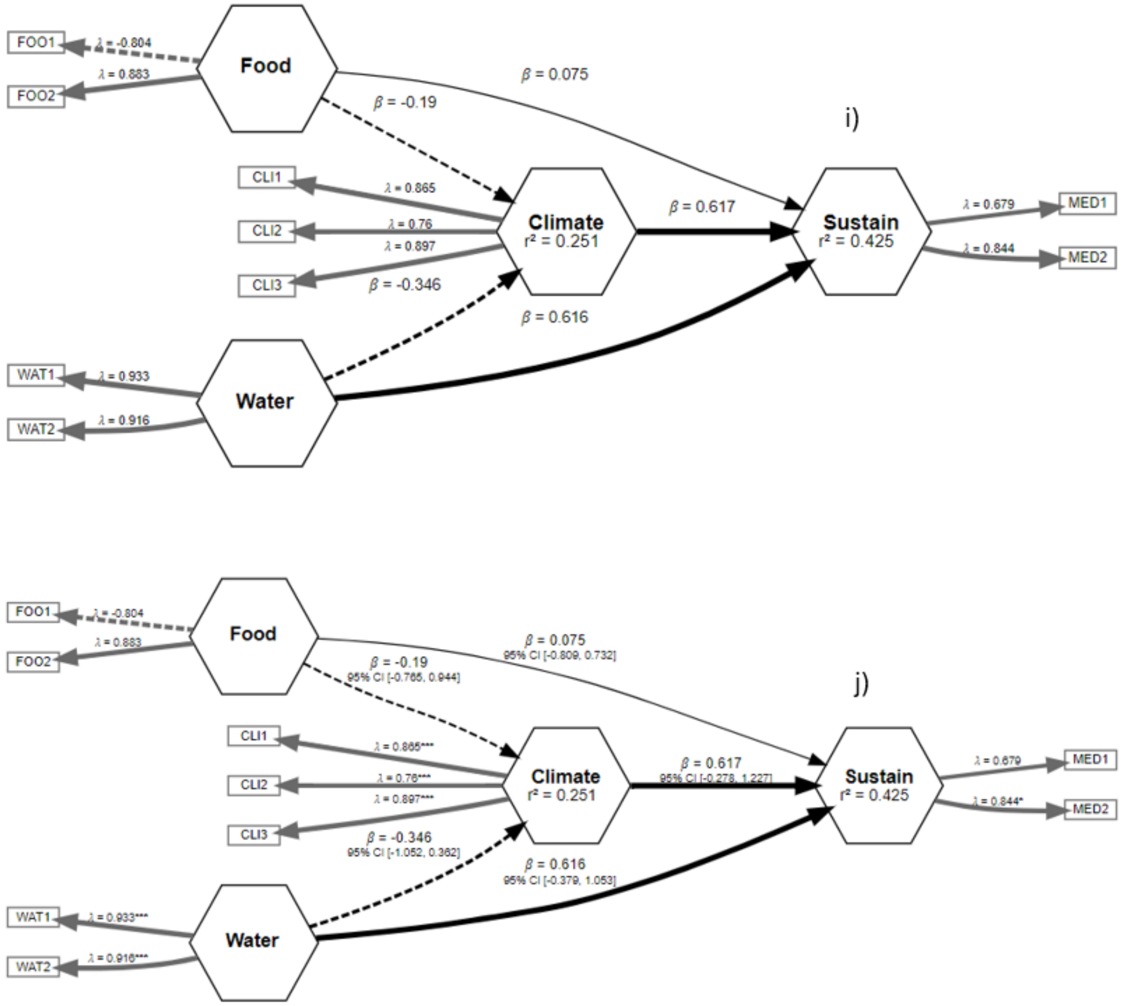

Figure 21: Relationship 2 for Vhembe District Municipality - water, food climate and sustainability model i) and the bootstrapped model j). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

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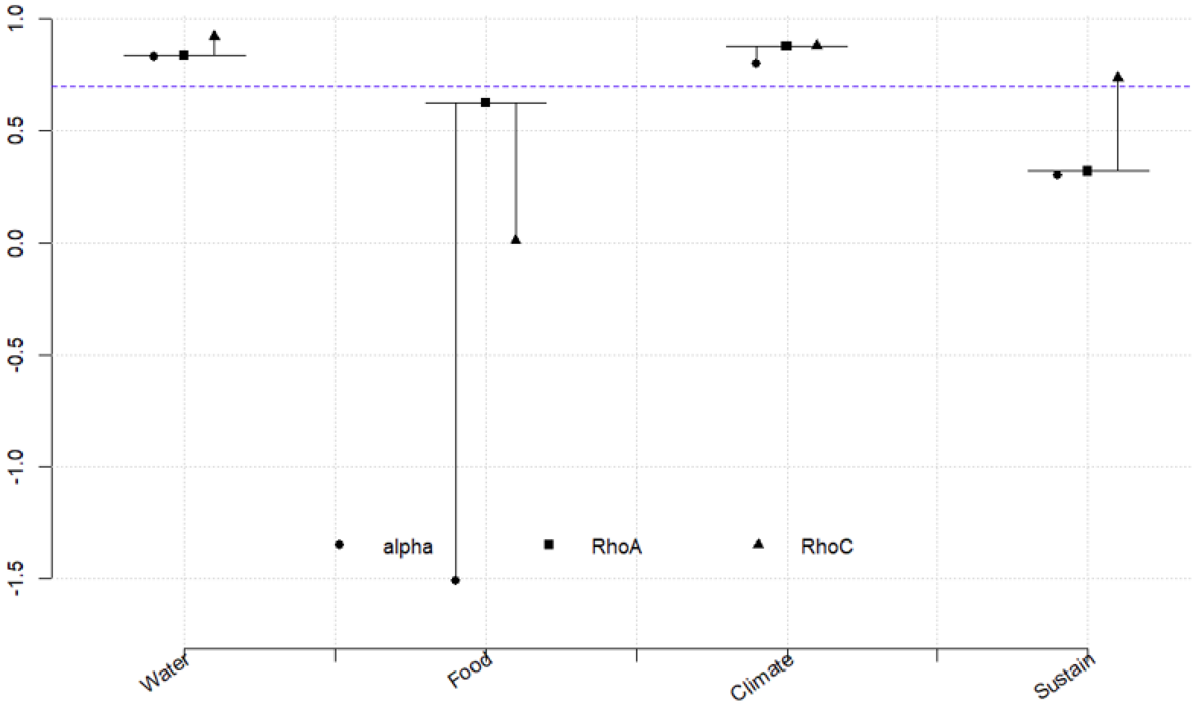

Figure 22: Reliability graph for relationship 2 – Vhembe District Municipality (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

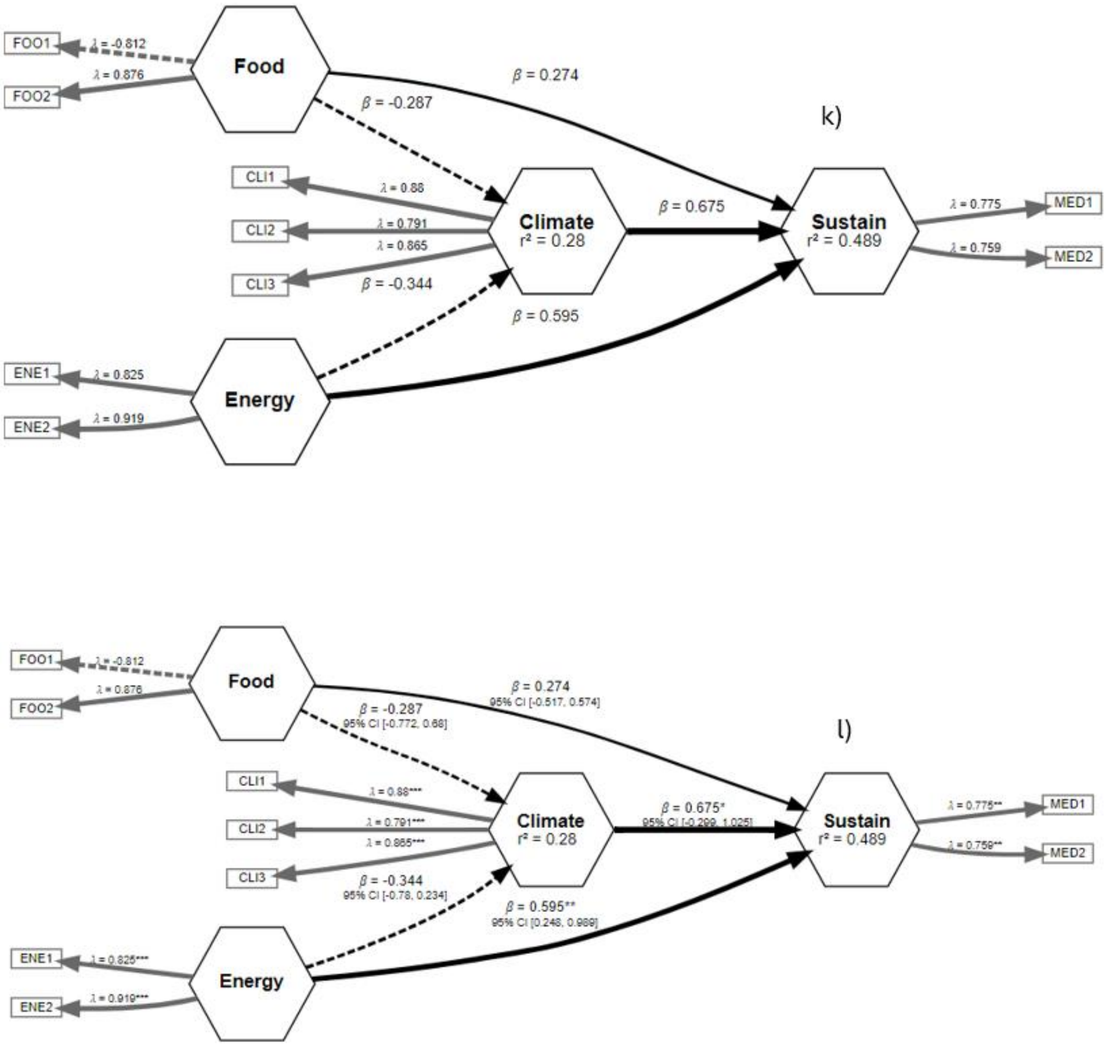

Figure 23: Relationship 3 for Vhembe District Municipality - Energy, food climate and sustainability model k) and the bootstrapped model l). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

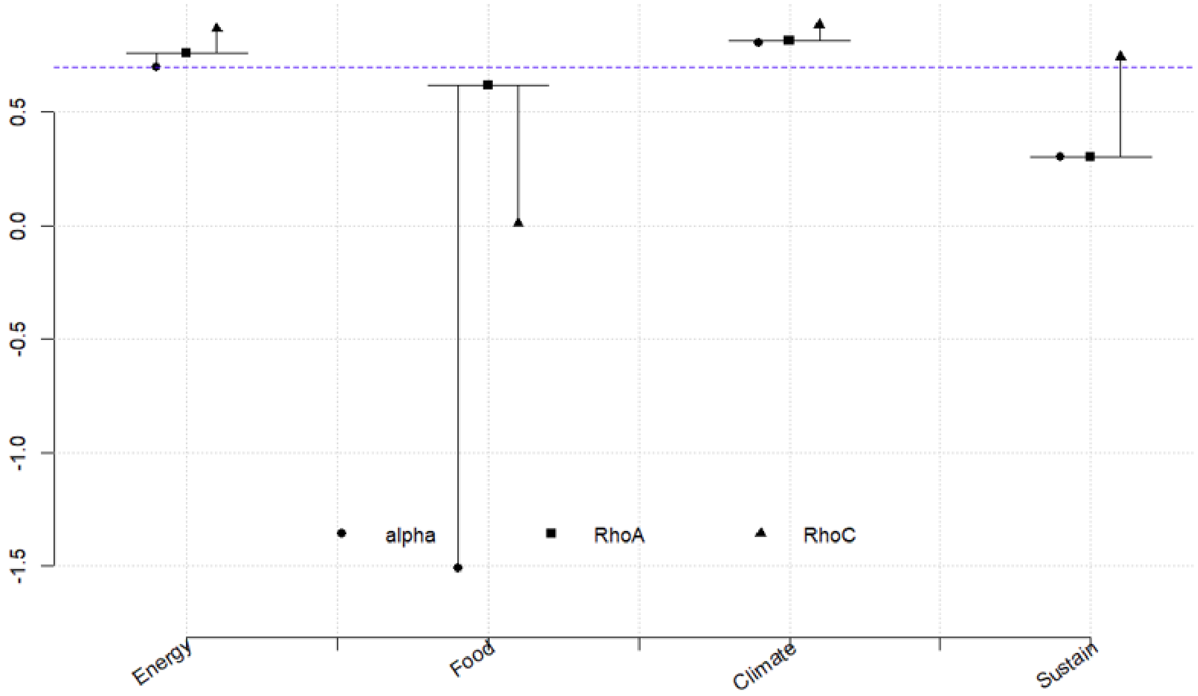

Figure 24: Reliability graph for relationship 3 – Vhembe District Municipality (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

Table 12: 5% confidence interval for mediated path for Vhembe District Municipality.

Mediation paths	Water, Energy, Climate and Sustainability			Water, Food, Climate and Sustainability			Energy, Food, Climate and Sustainability		
	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)
Water-climate-sustainability	0.34	-0.84	0.46	0.25	-0.70	0.26	-	-	-
Energy-climate-sustainability	0.25	-0.77	0.13	-	-	-	0.24	-0.68	0.21
Food-climate-sustainability	-	-	-	0.32	-0.60	0.61	0.29	-0.61	0.56
Climate-sustainability	0.39	-0.15	1.39	0.32	0.04	1.10	0.29	-0.29	1.02

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3.3.2.3. Both sites combined

Figure 25 demonstrates relationship 1, where both energy and water have an indirect effect on climate. The negative impact for energy is significant with a coefficient of β = −0.166 *** (asterisk is the significance level). A direct effect is observed from energy to sustainability, and an indirect effect is observed from water to sustainability. Moreover, a significant positive impact from climate to sustainability is evident with a coefficient of β = 0.448 ***. In relationship 1, water, energy, and climate show more reliability, as demonstrated in Figure 26.

Relationship 2 - water, food, climate, and sustainability are demonstrated in Figure 27. Food has a significant positive direct impact on both climate and sustainability. The significance level is more from food to climate than from food to sustainability, indicated by the coefficient of β = 0.404 *** and β = 0.137 *. Similar to relationship 1, climate is also directly linked to sustainability. Unlike food, water indicates an indirect link to climate and sustainability with a coefficient of β = −0.051 and a coefficient of β = −0.037, respectively. Water and climate show more reliability in this model, and food is the least reliable, as illustrated in Figure 28.

Lastly, relationship 3 is explored in Figure 29, where food is directly linked to climate and sustainability. In contrast, energy depicts an indirect negative impact on both climate and sustainability. The negative impact is significant from energy to climate with the coefficients of β = −0.126 *. Climate change significantly affects sustainability with a positive impact factor coefficient β = 0.396 ***. The reliability graph (Figure 30) shows that both energy and climate are reliable.

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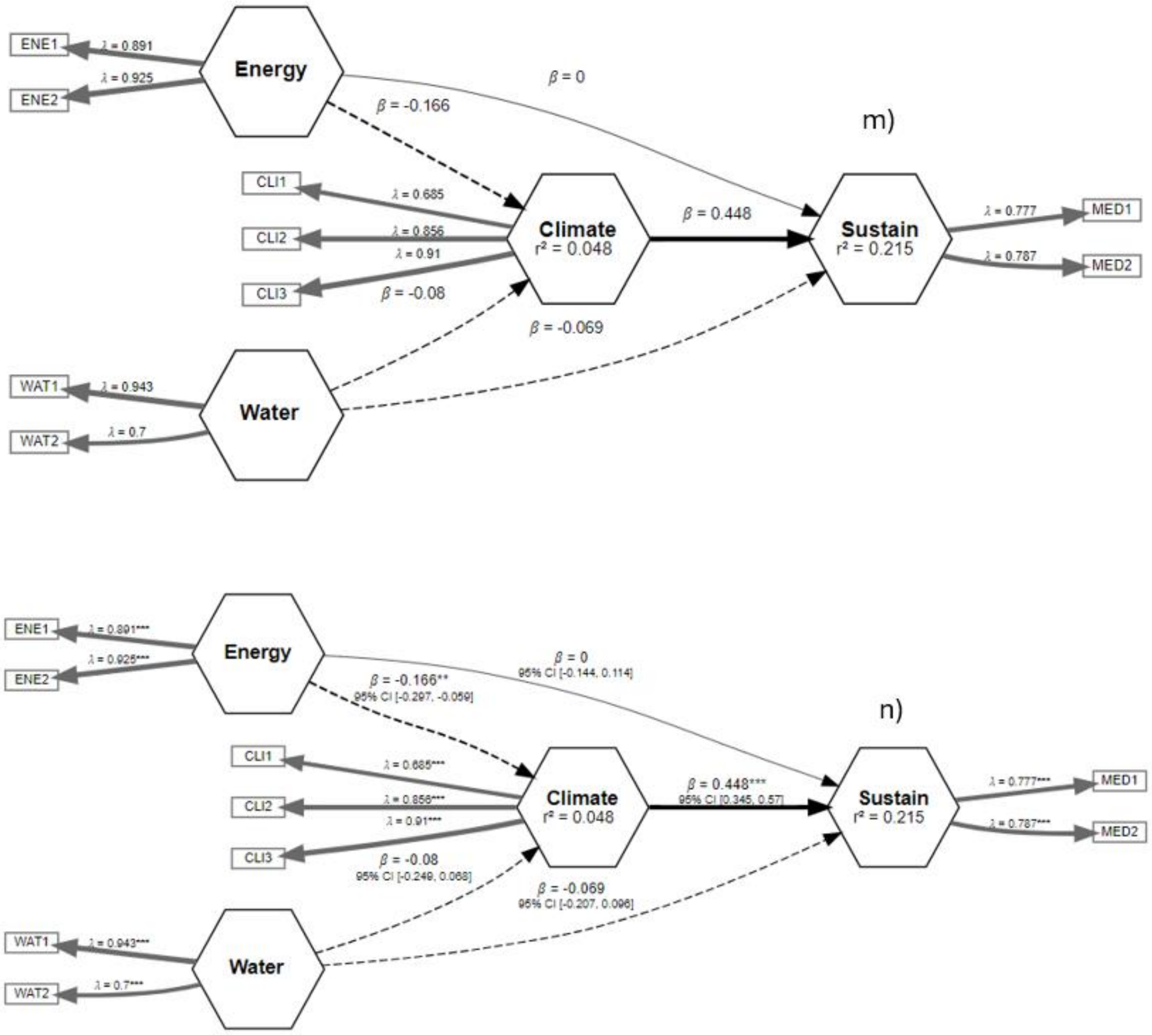

Figure 25: Relationship 1 for both sites - water, energy climate and sustainability model m) and the bootstrapped model n).

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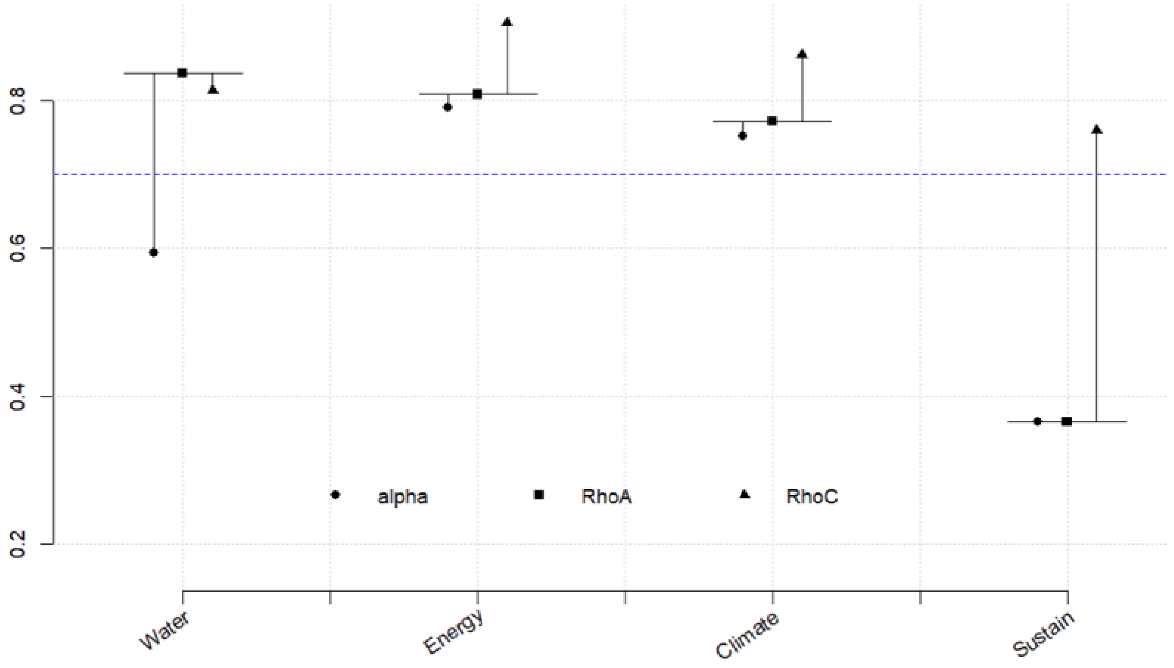

Figure 26: Reliability graph for relationship 1 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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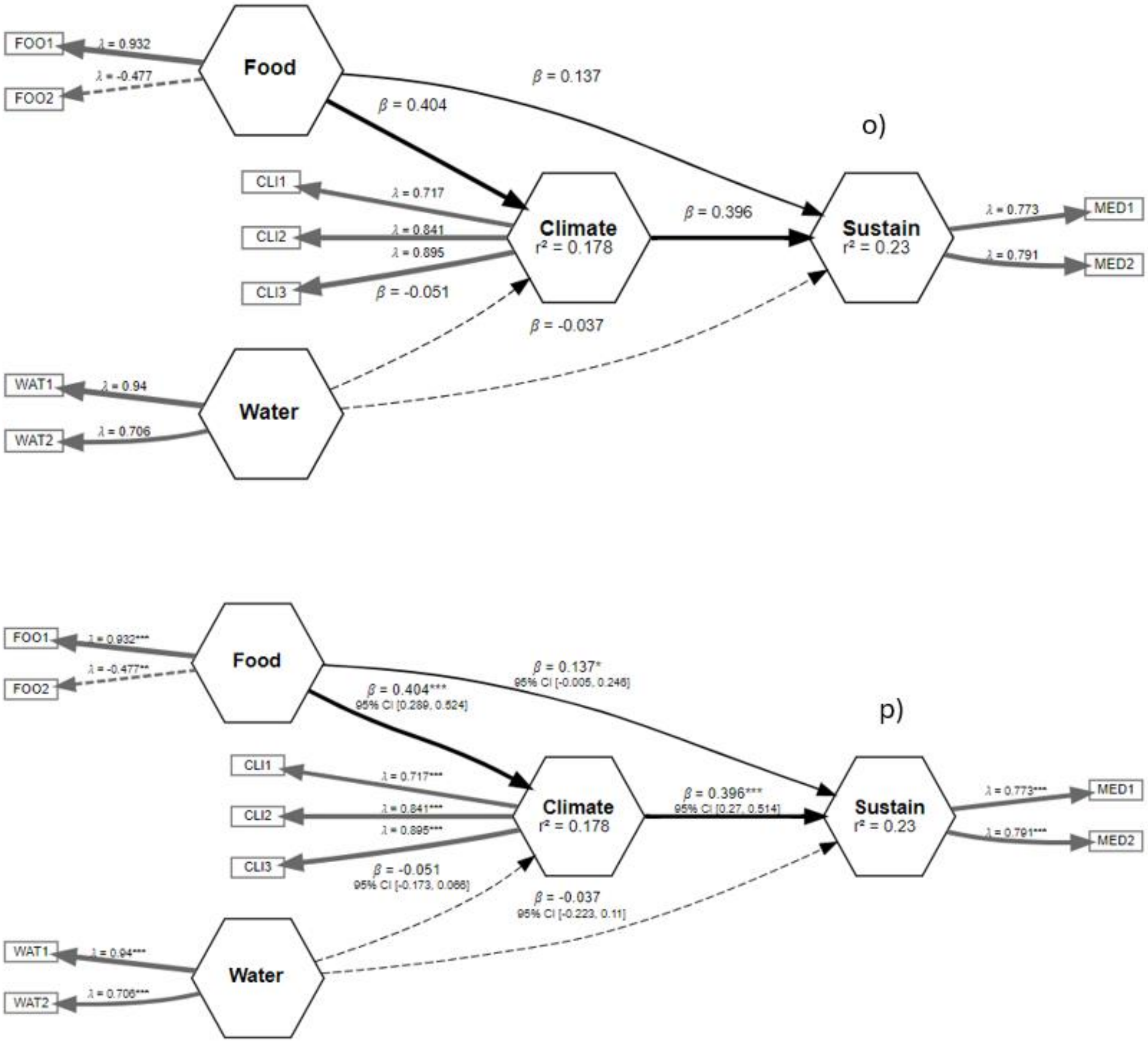

Figure 27: Relationship 2 for both sites - water, food climate and sustainability model o) and the bootstrapped model p). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

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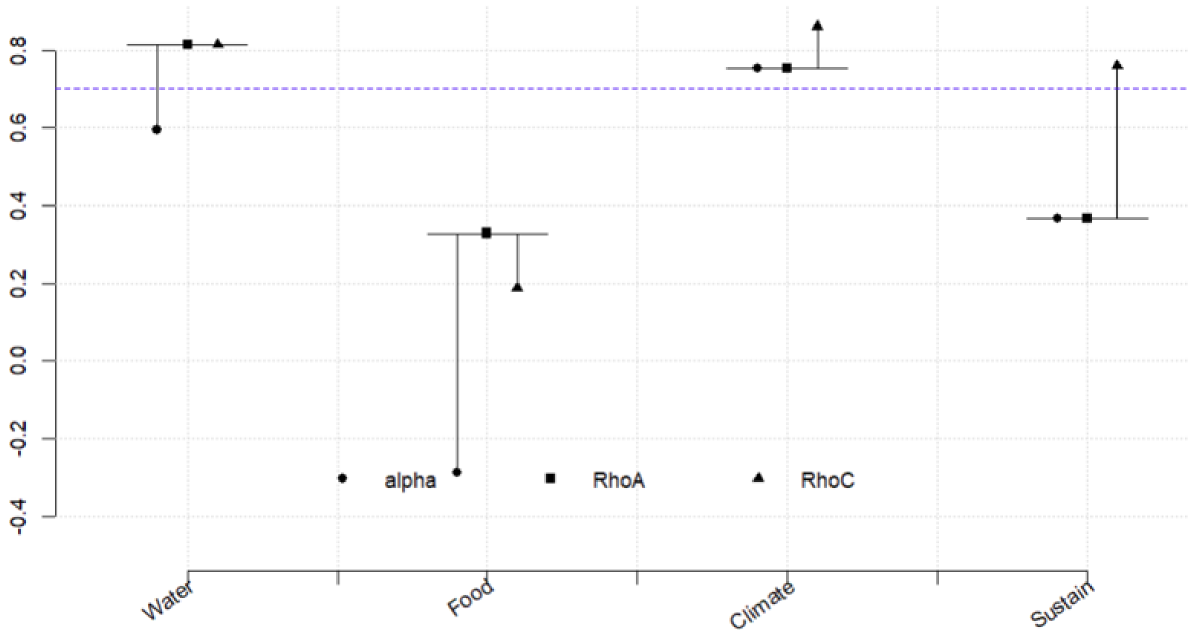

Figure 28: Reliability graph for relationship 2 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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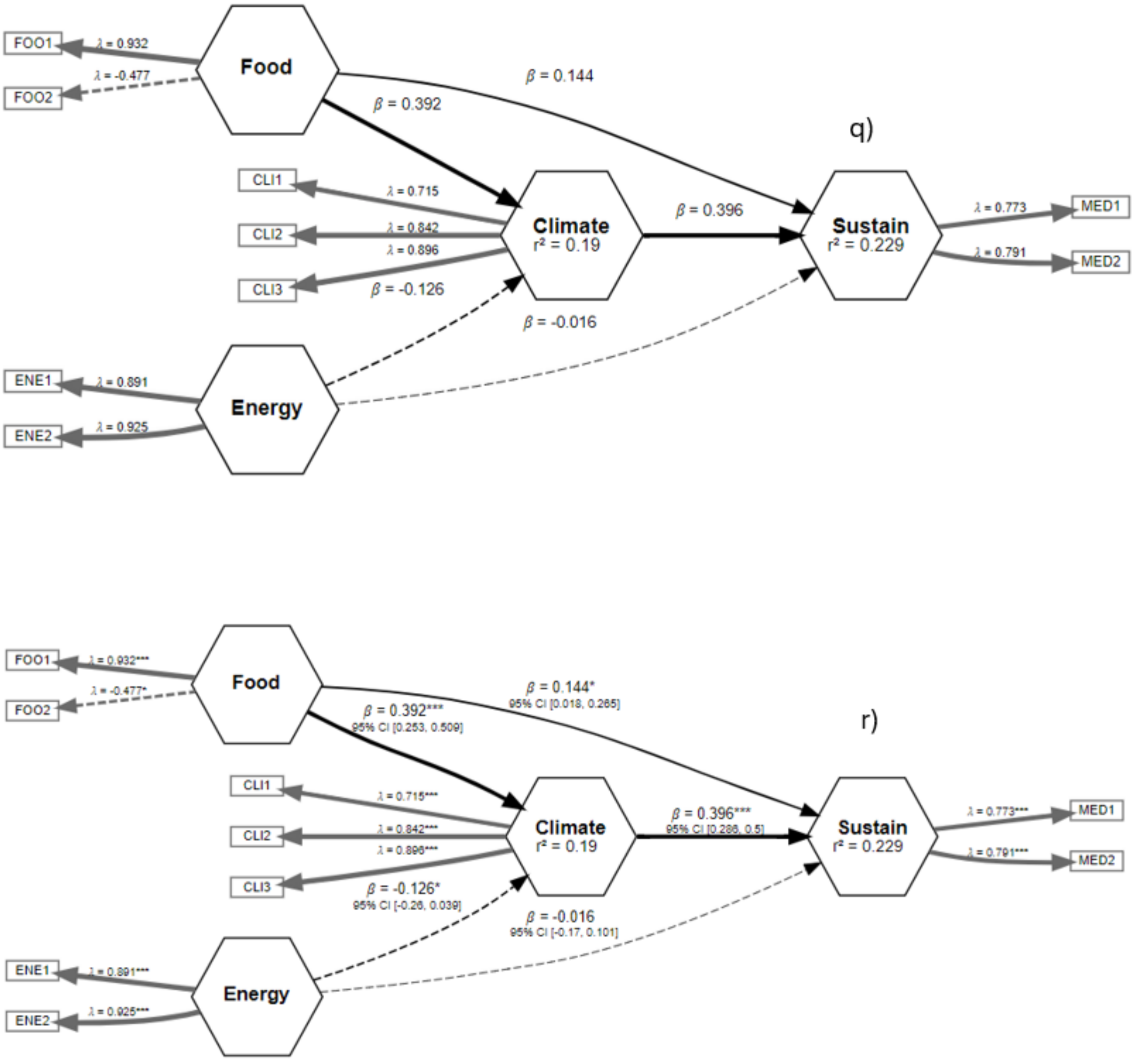

Figure 29: Relationship 3 for both sites - Energy, food climate and sustainability model q) and the bootstrapped model r). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

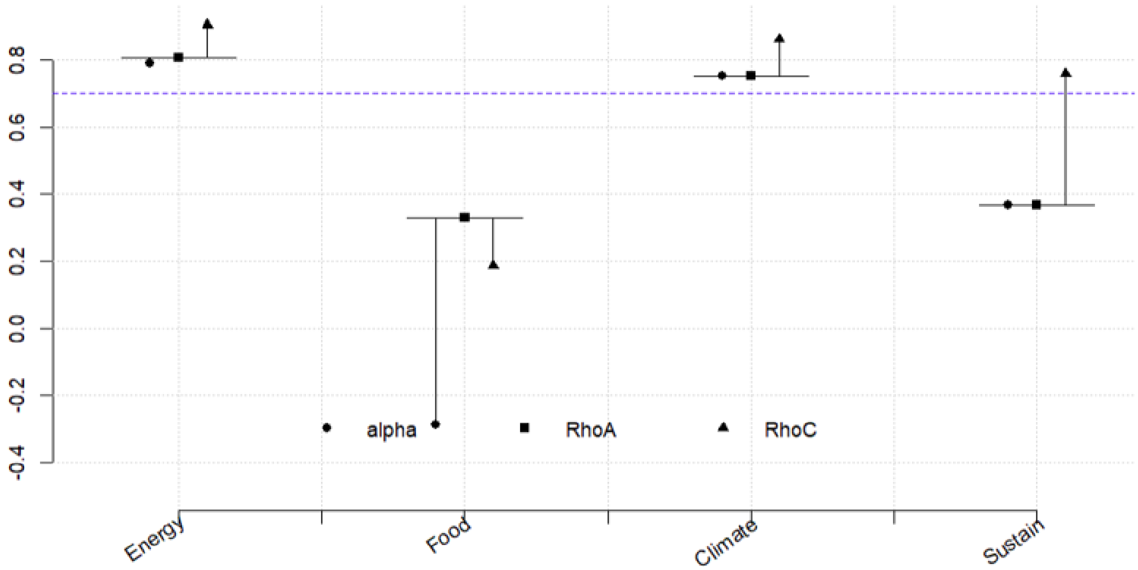

Figure 30: Reliability graph for relationship 3 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

Table 13: 5% confidence interval for mediated path for both sites.

Mediation paths	Water, Energy, Climate and Sustainability			Water, Food, Climate and Sustainability			Energy, Food, Climate and Sustainability		
	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)	Std	CI (25%)	CI (97.5%)
Water-climate-sustainability	0.04	-0.11	0.02	0.02	-0.07	0.02	-	-	-
Energy-climate-sustainability	0.03	-0.14	-0.01	-	-	-	0.03	-0.12	-0.00
Food-climate-sustainability	-	-	-	0.05	0.08	0.24	0.05	0.07	0.25
Climate-sustainability	0.07	0.32	0.59	0.06	0.28	0.53	0.07	0.23	0.52

3.4. DISCUSSION

The SEM framework does not determine causation between the variables (An, 2022); however, in this study, the SEM model showed with significant confidence that the water, energy and food sectors are closely interconnected under changing climate and sustainability but differently. Furthermore, the results for the selected sites (Narok County and VDM) show that climate and climate change have a significant direct impact on sustainability. Similar results are observed when we combined the two study sites.

The negative impacts influencing the three sectors manifest from the increased stress and scarcities of WEF resources, complemented by high rate of population growth, variations in resource consumption, including land-use patterns, and climate change (Abulibdeh and Zaidan, 2020). The current findings corroborate with numerous studies reported in literature, e.g., (Mabhaudhi et al., 2019, Nhamo et al., 2020, Nhamo et al., 2018, Botai et al., 2021, Rasul and Sharma, 2016 and Botai et al., 2024), mostly emphasizing the urgent need to focus on the sustainability of WEF nexus and the implementation of effective management plans that support an enhancement in WEF resource security.

Moreover, the results further showed that food security is directly impacted by changing climate, whilst interlinked to sustainability, a pre-condition for long-term food security. The results corroborate the studies by Meybeck et al (2017), a direct impact of climate change on food production and distribution, with changing precipitation patterns being the main contributing factor to the reductions in crops and agricultural yields was found. However, with energy the results give a different perspective to Meybeck et al (2017). The present study found that energy has a negative impact on climate (relationship 1 and 2), while it has a positive influence on sustainability. Contrary to Meybeck et al (2017), water and energy have indirect negative impacts on sustainable development. Such impacts are fundamental given that water and energy contribute towards poverty alleviation and economic development, thus supporting the sustainable development goals. These results point to a robust analysis of developmental options in the two study sites.

Considering all the relationships explored in this study, climate change is directly linked to a community's health, wellbeing and sustainable livelihoods, as proffered in the well documented SDGs. The World Meteorological Organization (WMO) reported a new record for daily temperatures (WMO, 2024) wherein the period from June 2023 to June 2024 indicated the warmest compared to recent years. South Africa and Kenya, like many African countries, are the

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most vulnerable to the impacts of climate change. Numerous studies have alluded that the frequency and magnitude of extreme weather and climate events in both countries are rising faster, overtaking the population capacity to manage the supply of key resources (e.g., water demand exceeding supply) and weather-related disasters (Schutte and Pretorius, 1997, Cole et al., 2018, Mulwa et al., 2021 and Munene et al., 2024). This global warming trend is expected to exacerbate extreme weather events' severity, frequency, and duration (Engelbrecht et al., 2021), such as heatwaves, droughts, floods, and thunderstorms. These extreme events threaten socio-economic, environmental well-being and sustainable development (Bouwer, 2017).

The report from WMO paints a clear picture that climate has a direct impact on sustainability and livelihoods of communities. Water, Energy and Food resources are variables in assessing the impact of climate change and sustainability. The result of the present study shows that efforts to ameliorate the impacts of climate change on one sector alone cannot improve WEF resources security as a whole and that external factors may disturb the WEF systems. Consequently, WEF resources security could be effectively ascertained when improving indicator proxies of the WEF and climate with the highest influence. A cross-sectoral, cohesive, and integrated perspective is embraced by solutions that use a WEF nexus approach, representing fundamental shift from conventional sectoral approaches (Botai et al., 2024).

Reaching the Sustainable Development Goal targets pertaining to Goals 2, 6, and 7 (food, energy, and water) is essential to achieve global aspirations for a sustainable future, which include planetary health and resource security (Mabhaudhi et al., 2019 and Nhamo et al., 2020). To accelerate progress towards achieving the SDGs, transformative, cross-sectoral, and circular approaches that improve resource use efficiency and sustainability must be adopted (Mabhaudhi et al., 2019). Thus, recognizing and appreciating the interlinkages between WEF resources is the first step towards achieving the SGDs. The study provides vital cases to contribute to this important research discourse, considering that WEF resources form the basis for the SDGs, which is essential for the 2030 global agenda (Thuo et al., 2017). The present study has generally established that WEF security is closely related to the sustainability of humans, the environment and the economy. Inadequate supply or access to WEF resources can cause several health issues due to poor water quality, an unhealthy diet, and an intermittent lack of energy. Such effects become greater when these variables are combined

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3.5. CONCLUSION

Many African countries still have demand and accessibility challenges to WEF resources. For this reason, a comparative study of two different sites (Narok County and Vhembe District Municipality), yet exhibiting similar socio-economic, environmental and technological circumstances was undertaken. The SEM model explained the explicit or implicit impacts of climate change on WEF resources, indicating that water and energy and sustainability are affected by climate change, while food is directly influenced by climate change. While these variables are mediating, climate and sustainability have a direct pathway. The SEM simulations showed, with a significant 95% confidence interval, that the alternative hypothesis is indeed true i.e., that there exists interdependence between the state of climate and WEF resources. Results from this study illustrated that there exist synergies in the WEF resources rather than combining all processes into a single index to investigate subsystem synergy. Overall, the SEM modelling framework is an effective methodology duly suited to exploring interactions among the WEF nexus and the changing climate to advance the WEF nexus research field. Our exploration of interactions of WEF resources from the perspective of SEM contributes to the body of knowledge on complex nonlinear systems analysis. Policymakers still view the WEF nexus as theoretical, and its relevance is not well vested in society. Policy and decision makers can use the analysis from this study to help them scale up and implement the WEF nexus approach. This study asserts that an integrated approach involving political systems, different stakeholders, and role-players must collaborate in order to define and derive appropriate trade-offs with the WEF resources value chain, particularly in light of the current changing climate, in order to achieve sustainable development within the WEF sectors. Furthermore, it is recommended that integration of the institutions charged with policy making and implementation of WEF-nexus approaches be strengthened. Lastly, it is hoped that the study brings to the fore the important value of wide stakeholder participation prioritizing citizens to promote knowledge sharing, bottom-up solutions, and conflict resolution.

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CHAPTER FOUR: ANALYSIS OF THE PROJECTED CLIMATE IMPACTS ON THE INTERLINKAGES OF WATER, ENERGY AND FOOD NEXUS RESOURCES IN NAROK COUNTY, KENYA AND VHEMBE DISTRICT MUNICIPALITY, SOUTH AFRICA

Having established the linkages between the WEF and the sustainable development options in the study sites, it is vital to formulate visible options to support resilience in the communities. This study therefore avers that in the current changing climate, there is a need to develop WEF nexus-oriented systems capable of mainstreaming climate smart approaches now and in future. The main aim of this chapter is to demonstrate how climate change will impact the interlinkages of the WEF resources in the study areas through examining the potential effects of projected hydroclimatic extremes of past, present and future water, energy and food availability and access. Overall, this chapter illustrates the downscaled climate change scenarios and integrates a modeling framework designed to depicts the perceptions of future climate change impacts on communities based on questionnaires and first-hand accounts. Analysis results point to a concerted efforts of multi-stakeholder engagement, access and use of technology, understanding the changing business environment, integrated government and private sector partnerships as well co-development of community resilient options including climate change adaptation and mitigation in the changing climate.

4.1. INTRODUCTION

The security of water, energy and food is a key priority as the three resources are stressed globally, due to the recurrence of extreme weather events, depletion, degradation and increasing demand from a growing population, The three sectors (water, energy and food) are intricately interconnected as energy generation requires water in large volumes for fuel production, mining, hydropower and power plant cooling. On the other hand, energy is also needed for pumping, treating and distributing water and for collecting, treating and discharging wastewater. Simultaneously, water and energy are needed for food production, while crops such as maize, soybean and sugarcane are now being found to have alternative uses as biofuels. These mutual interconnections are referred to as the water-energy-food (WEF) nexus.

The African continent is experiencing heightened competition among communities for these key resources (Muhiwa et al., 2023 and Oliver and Nnamdi, 2024). The relationship between the water-energy-food (WEF) resources and the African economies has become increasingly significant as the continent faces increased competition for such critical resources among communities (Molefe and Inglesi-Lotz, 2023). The continent faces multiple stresses, including a poor economy, threats posed by climate change, poor governance and a lack of recovery strategy after the COVID-19 fiasco. Since the WEF nexus underpins sustainable development goals (SDGs 2, 6, 7 and 13), numerous studies have been undertaken in Africa. A study by Molefe and Inglesi (2023) investigated the variable relationship between water, energy, food and economic conditions for the big 5 African countries (South Africa, Nigeria, Kenya, Angola, and Ethiopia). Molefe and Inglesi (2023) explained the significance of WEF interlinkages while acknowledging the increasing demand for the three resources due to the continent's expanding population and changing lifestyles on dietary requirements. The findings showed synergies between the three sustainability demonstrations for the five countries, which have important policy implications for the continent’s current and future developmental conditions.

In Kenya, Wakeford (2017) examined the global and national effects of the WEF nexus, such as population growth and rapid urbanisation. Moreover, the study identified Kenya’s WEF vulnerabilities and risks, including climate variability and international food and oil price consternation. Meanwhile, Kanda et al (2023) analysed the policy interventions aligned with WEF resources and underscored that while policies are in place, there is a need for more coordinated approaches across sectors.

A framework to align the WEF nexus with SDGs, specifically SDGs 2, 6, and 7, while assessing the state of the WEF nexus and recommending actions such as data sharing and standardisation, cross-sector collaboration, private sector involvement, public education, and consideration of climate change impacts has been proposed by Mabhaudhi et al (2018). Moreover, David et al (2024) explored WEF resource management in South Africa, advocating for a digital framework to support development and results across these sectors.

These studies collectively identify common challenges, such as policy misalignment, sector-specific silos or linear approaches, resource misallocation and inefficiencies, while advocating for integrated policy framework, cross-sector collaboration, stakeholder engagement, improved governance, and investment in infrastructure and technology. The growing population in Africa is driving an increased demand for water, energy, and food resources (Molefe and Inglesi, 2023). According to Botai et al (2024), the climate crisis will likely increase the demand for these resources. A study by Zwane et al (2024) introduced the structural equation model as an innovative methodology over a single equation modelling framework in analysing variables that have complex interrelationships, facilitating advanced WEF nexus resource governance. The analysis concluded with high confidence that while the food, energy, and water sectors are closely related, their effects on sustainability and the environment differ.

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2021), the global surface temperatures during the first two decades of the 21st century (2001 – 2020) were about 1ºC higher than the pre-industrial period (1850 – 1900). Notably, since 1970, the increase in global surface temperatures has been more rapid than in other 50-year periods over the preceding two millennia. This increase in average temperature has been linked to intensified extreme weather events such as heatwaves, wildfires and droughts (Field and Barros, 2014).

Specifically in South Africa, studies have alluded to increased minimum and maximum temperatures (Engelbrecht et al., 2015 and Mbokodo et al., 2020) and record-high temperatures consistent with global warming (McBride at al., 2021). In Kenya, it has been observed that climate risks pose a significant threat to Kenya's sustainable development goals, particularly because the economy of Kenya is largely dependent on rainfed agriculture and tourism, both of which are susceptible to extreme weather events attributed to climate variability and change (Ihinegbu, 2021). Research has also demonstrated that erratic rainfall and increased drought have reduced agricultural productivity, water scarcity, and food insecurity in many areas of Kenya (Mulwa and Fangninou, 2021). Similarly, extreme weather events such as floods and heat waves impact the tourism sector by affecting wildlife ecosystems and the infrastructure necessary for tourism (Korir and Ngenoh, 2019). Such problems require integrated policies and adaptive strategies to reduce risks and promote resilience in major economic sectors.

Africa is highly vulnerable to global changes in climate conditions because of its low adaptive capacity, limited access to technology and high sensitivity to climatic factors (Korir and Ngenoh, 2019). These climate-related hazards often lead to loss of life, social disruption, and economic hardships, as reported in (Botai et al., 2024).

In South Africa, a case occurred in January 2022 when several news outlets in South Africa reported a severe heatwave in the Northern Cape Province, with temperatures reaching 41°C over a wide area, resulting in heatstroke-related deaths of seven farm workers. Additionally, the country faces highly variable rainfall patterns and more severe storms (Botai et al., 2024), as seen in the April 2022 KwaZulu Natal floods, which claimed over 400 lives and damaged property and infrastructure. The water supply for domestic, agricultural, and industrial uses has been severely

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impacted by the recent severe drought in several regions, particularly the Western and Eastern Cape provinces (Botai et al., 2017, Botai et al., 2016, Botai et al., 2021). The intensity and frequency of droughts and floods are affecting the economies of various provinces in South Africa, and this has a series of implications, especially for job creation programmes initiated at provincial and local levels.

On the other hand, in April of 2024, several news outlets reported heavy rains hit Kenya, affecting people in 33 of the 47 counties. The floods in Kenya left people devasted, wiped out houses and, in some areas, resulted in the loss of lives (Engelbrecht et al., 2015). According to Molefe and Inglesi (2023), climate change has been associated with a decrease in the likelihood of rainfall and a rise in its intensity, leading to an increased frequency of flooding, posing a significant threat to Kenya and South Africa's food and water security, human health, economy, society, and environment (Omambia et al., 2009). Prolonged drought and famine have currently left over 10 million people faced with starvation, while floods and resurgence of pests and diseases have been noted in other parts of the country (Almulhim et al., 2024). The interconnectedness of these systems underlines the need to adopt integrated resource management and adaptive strategies focused on regional specifics in climate and socioeconomic conditions (Almulhim et al., 2024). Given climate projections that indicate the continuance of these challenges, comprehensive policies are needed that balance synergies and trade-offs within the nexus of water-energy-food, enabling sustainable development and increasing resilience to climate change in vulnerable areas (Engelbrecht et al., 2015).

Furthermore, climate change has increased the vulnerability of communities in Narok County and Vhembe District Municipality through unstable changes in meteorological variables, with many rural livelihoods dependent on agriculture and natural resources (Bazilian et al., 2011). The prolonged drought and heavy rainfall combined have broken the fragile equilibrium that enhances water shortages and decreases agricultural production, adding food insecurity (van Vuuren et al., 2012). Climatic changes strain the economic sector on local economies and heighten social issues such as displacement, migration, and resource conflicts (Adom et al., 2022).

The WEF resources are closely linked, with changes in one often affecting the others. Water is crucial for food production and a shortage can result in crop failure and food insecurity. Similarly, energy is required for water extraction, treatment and distribution. Therefore, disruption in energy can limit water access. Lastly, food production relies heavily on energy for farming, transportation and storage. Thus, energy shortages can decrease agricultural productivity. A decrease or

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shortage in any of these resources can cause cascading impacts, leading to more strain on the others. Hence managing WEF resources in an integrated manner is crucial to addressing the challenges posed by climate change and ensure resilient communities (van Vuuren et al., 2012 and Adom er al., 2022)

The primary aim of this study is to illustrate how climate change would affect the interlinkages of the WEF resources in Narok County (Kenya) and Vhembe District Municipality (South Africa) study sites by analysing the potential effects of projected hydroclimatic extremes of past and present and future water, energy and food availability and access. To achieve the aim, the following objectives are envisioned: a) illustrate the statistically downscaled climate change scenarios for annual surface temperature and annual total rainfall as well as the two extreme indices (Consecutive Dry Days and Simple Daily Intensity Index), b) incorporate a modelling framework designed to depicts the perceptions of future climate change impacts on communities based on questionnaires and first-hand counts. The framework is designed to be future oriented, integrating climate projections to ensure proactive planning and resilience. Moreover, developing accurate climate scenarios requires a strong foundation in understanding the baseline climate impacts. This entails gathering insights from respondents who have experienced climate-related changes firsthand. Their viewpoints offer valuable qualitative and quantitative data on past and present trends, vulnerabilities and adaptive responses. Examining these interconnections, the study will shed light on the challenges and opportunities involved in devising integrated, sustainable strategies that enhance resilience and protect these vital resources in an uncertain climate.

4.2. MATERIALS AND METHODS

4.2.1. Bias Correction Approach

The projected temperature and rainfall presented in this study are based on the Coupled Model Intercomparison Project Phase 5 (CMIP 5) Global Climate Models (GCMs) (IPCC., 2021) with specific focus on the selected projected greenhouse gas concentration pathways, also used as basis in the South African Weather Service (SAWS) Climate Change Atlas (https://www.weathersa.co.za/home/climatechangeatlas) and the Kenya County Climate Risk Profile: Narok County. For stakeholder engagement analysis, the questionnaire described under Chapter 2 (section 2.2.2.2) and Chapter 3 (section 3.2) was utilized. Furthermore, the SEM used in chapter 3 and according to Zwane et al., (2024) was used.

The model outputs are based on the IPCC “Representative Concentration Pathways (RCPs)”. Only two RCP scenarios were considered in this study, the RCP 4.5 “moderate scenario” and RCP 8.5 “business as usual scenario” (where no significant action is taken to curb greenhouse gas emissions), also defined as the addition of 4.5 W/m^2 and 8.5 W/m^2 radiative forcing in the atmosphere respectively by the year 2100 (IPCC, 2021). Selecting the two RCP scenarios (RCP 4.5 and RCP 8.5) provides a sensitive test of the extent to which mitigation action or its absence may shape future climate conditions.

The analysis utilizes historical and projected simulations from nine GCMs, as listed in Table *14*. Note that output from these GCMs is in a relatively coarse resolution. To refine to a higher resolution, dynamical downscaling was employed, achieving a finer resolution of 0.44°×0.44° (± 50km x 50km) using the Rossby Centre Regional Atmospheric Model (known as the RCA4 model) from the Swedish Meteorological and Hydrological Institute (SMHI) (WRC report K5/2247/1, 2016 and WRC report 3068/1/23, 2023). Simply put, the nine GCMs in Table *14* provided boundary input for the RCA4.

For the climate change projections, outputs from the historical or reference period (1976-2005), and projected time intervals, spanning the near-future, defined as the period starting from 2036 – 2065; and the far future, spanning from 2066 – 2095 were considered. An ensemble model to increase the skill, reliability, and consistency of output was formulated from the nine models in Table *14*. These model ensembles were created by use of the Simple Multi-model Averaging (SMA) technique (Georgakakos et al., 2004). The SMA approach can be described as:

$$(Q_{SMA})_t = \overline{Q_{obs}} + \sum_{i=1}^{N} \frac{(Q_{sim})_{i,t} - (\overline{Q_{obs}})_i}{N} \qquad (1)$$

where $(Q_{SMA})_t$ is the multi-model variable (e.g. precipitation, minimum or maximum temperature) simulations from CORDEX-Africa models derived using SMA at time *t*, $(Q_{SMA})_{i,t}$ corresponds to the i^{th} model variable simulation for time *t*, $(\overline{Q_{sim}})_{i,t}$ is the time average of the i^{th} model variable simulation, $\overline{Q_{obs}}$ corresponds to the observed average variable and N represents the number of models under consideration.

Table 14: CMIP5 GCMs used as boundary conditions for high resolution simulations of approximately 0.44° × 0.44° using the RCA4 Regional Climate Model (RCM).

Model	Institute (country)	Reference
CanESM2m	CCCMa (Canada)	Arora et al. (2011)
CNRM-CM5	CNRM-CERFACS(France)	Voldoire et al. (2013)
CSIRO-Mk3	CSIRO-QCCCE(Australia)	Rotstayn et al. (2013)
IPSL-CM5A-MR	IPSL(France)	Hourdin et al. (2013)
MICRO5	AORI-NIES-JAMSTEC (Japan)	Watanabe et al. (2011)
HadGEM2-ES	Hadley Centre (UK)	Collins et al. (2011)
MPI-ESM-LR	MPI-M(Germany)	Ilyina et al. (2013)
NorESMI-M	NCC(Norway)	Tjiputra et al. (2013)
GFDL-ESM2M	GFDL (USA)	Dunne et al. (2012)

4.2.2. Case Study: Model Validation against Observations

The temperature and rainfall climate projections were generated after validation of the model output; this is when the model performance in simulating the climate system is assessed. Historical ensemble mean simulation spanning from 1979 to 2005, derived from the nine RCA4 Regional Climate Model (RCM) members were compared with observational data from the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2011. SAWS, 2017) for precipitation and the NOAA GHCN_CAMS Land Temperature Analysis for observed temperature (Fan and van den Dool, 2008. SAWS, 2017). From literature, numerous studies (SAWS 2017 Climate Change reference Atlas, CSIR Green book, and Mutige et al, 2018) verified similar models for South Africa. The verified data at a national/ country spatial resolution was used for this study. The Kenya risk climate profile verified 32 models of those 9 are selected in this study. The models accurately captured the spatial distribution of rainfall and temperature in both the study sites. From the national spatial scale, we used the remapping technique to extract the nearest Neighbourhood.

Various bias corrections algorithms have been developed. The most bias correction approaches used in climatology is the quantile mapping (Zwane, 2019, Matthew et al., 2016 and Adeyeri et al., 2020). The quantile mapping objective is to map the source distribution quantiles to target distribution quantiles thereby correcting biases in individual climate variables and disregarding the dependencies and correlation between different variables (Zwane, 2019, Adeyeri et al., 2019 and Rai et al., 2013). The use of climate change scenarios from Global Climate Models (GCMs) have been widely used as the source of constructing information on changing climate and examining the impact of climate change.

The data used in this study is dynamically downscaled, however the downscaled output often associated with systematic errors or biases. The statistical bias correction algorithms are used to correct the systematic biases. The results after bias correction are more representative of observations. To accurately evaluate how climate change is affecting people and environmental resources, bias correction of climate model projections is necessary (Matthew et al., 2016). Table *15* show seven stations where the GCMs were downscaled to in Limpopo using daily rainfall, minimum and maximum temperature data acquired from SAWS for the period of 1985 – 2022. On the other hand, Table *16* shows nine stations from Narok Country acquired from TAHMO weather stations (through TWIGA project from SAWS) acquired at hourly temporal resolution and were converted to daily values for rainfall and temperature. These stations are distributed mostly in national park, which include Simba Hills, Maasai Mara, Mount Kenya, Aberdare and Chyulu.

To check the correlation between SAWS stations and TAHMO stations we performed three correlation coefficient tests, namely: Pearson, Kandall and Spearman. Three TAHMO stations and three SAWS stations in Gauteng were selected for the period 2019 – 2022. In the comparison analysis we assessed the outliers on the data and removed them. Furthermore, we replaced the missing values with the median. From the three coefficient tests, we used the Spearman which yielded the best results compared to Pearson and Kendall for both rainfall and temperature. Figure 31 indicates the correlation of SAWS and TAHMO stations for temperature (red positively correlated and light blue show negative correlation). SAWS and TAHMO stations are significantly and highly correlated, between 96% and 97% for temperature maximum as indicated Figure 32. Shown in Figure 33 is the correlation for SAWS and TAHMO stations for rainfall indicating positive correlation. Meanwhile Figure 34 demonstrates the significant correlation between SAWS and TAHMO stations. For rainfall the stations have between 60 – 70 % correlation (significance indicated by asterisk).

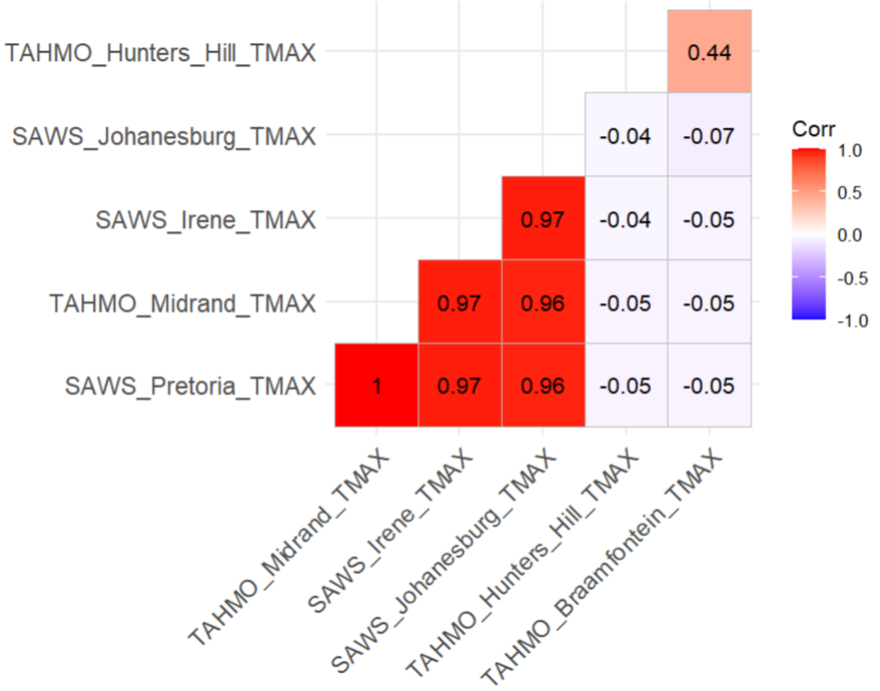

Figure 31: SAWS station vs TAHMO station correlation for temperature maximum.

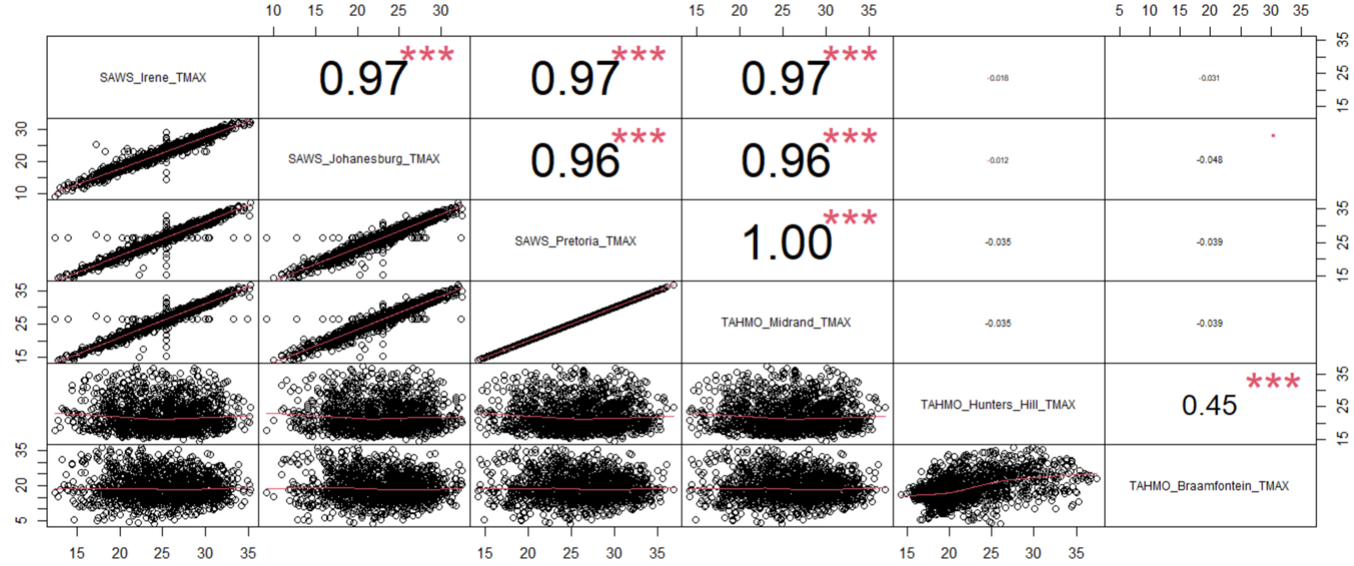

Figure 32: SAWS station vs TAHMO station showing significant correlation for temperature maximum (asterisk indicates significant correlation).

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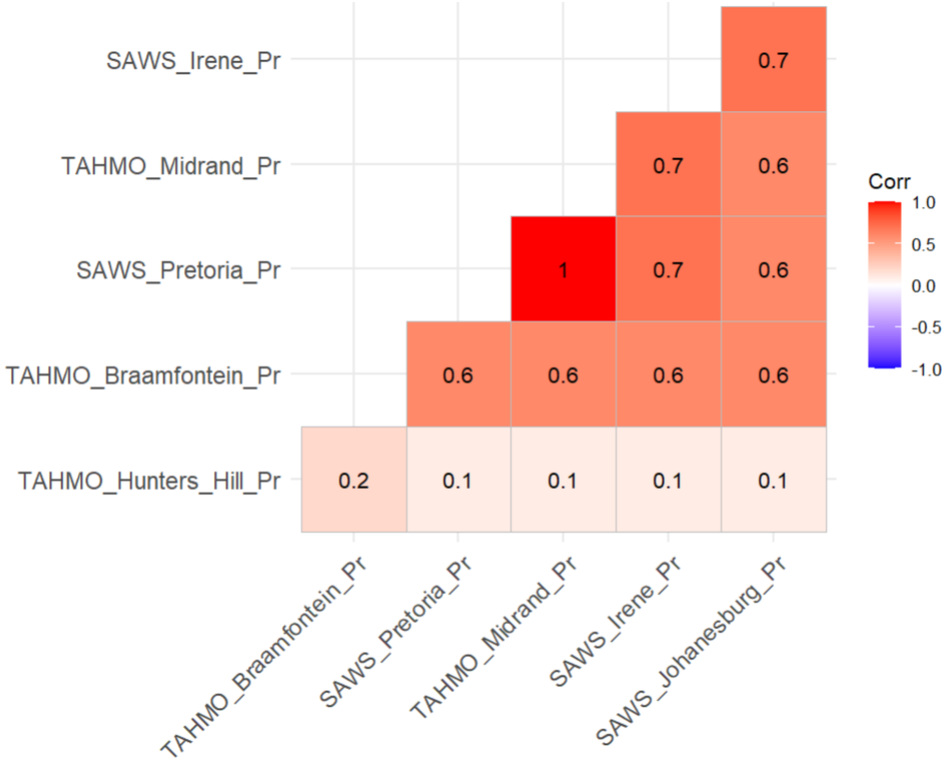

Figure 33: SAWS station vs TAHMO station correlation for rainfall.

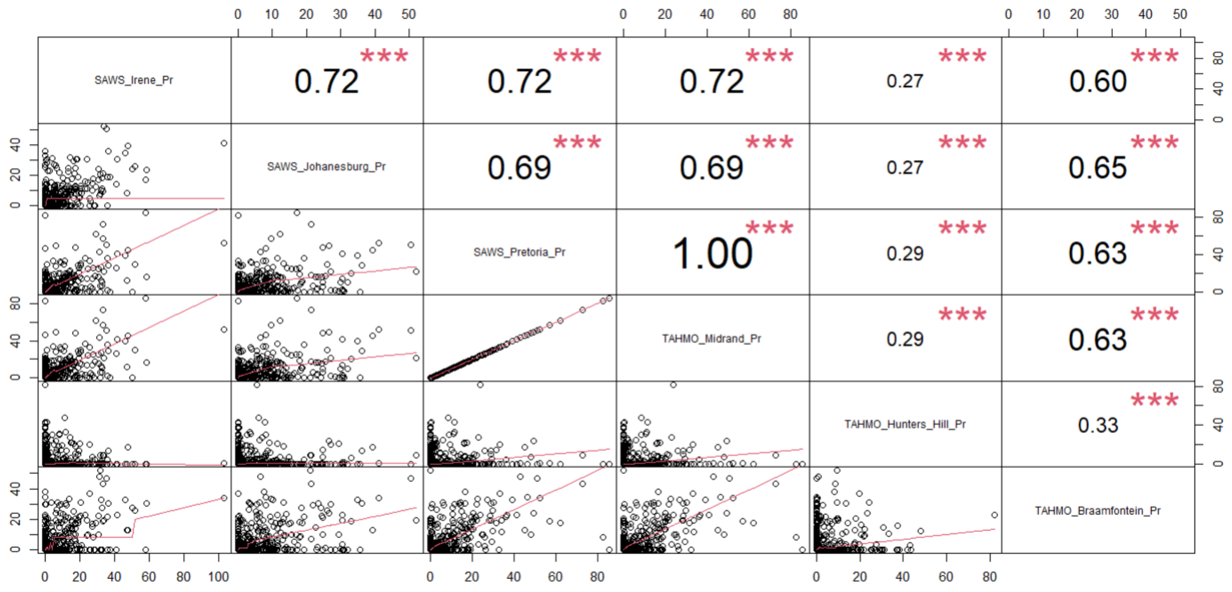

Figure 34: SAWS station vs TAHMO station showing significant correlation for rainfall (asterisk indicates significant correlation).

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Figure 35 and Figure 36 show results of quantile bias corrected data for Limpopo and Kenya respectively derived from the ensemble CMIP5 GCMs-RCMs in Table 14.

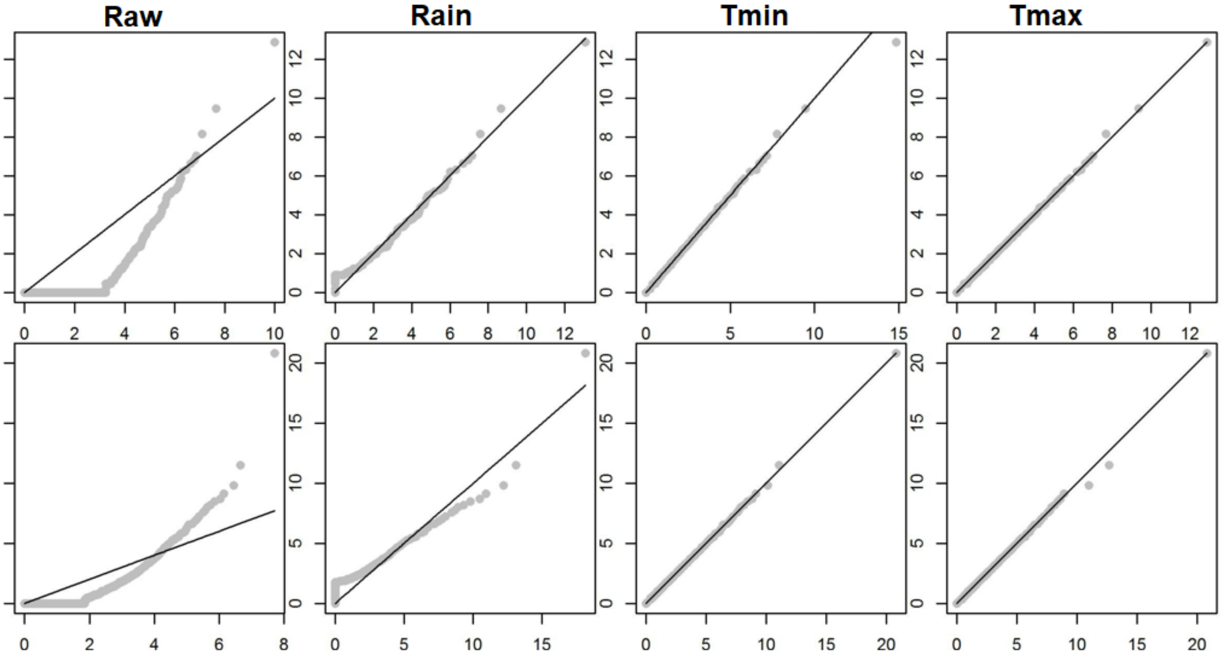

Figure 35: Limpopo bias corrected.

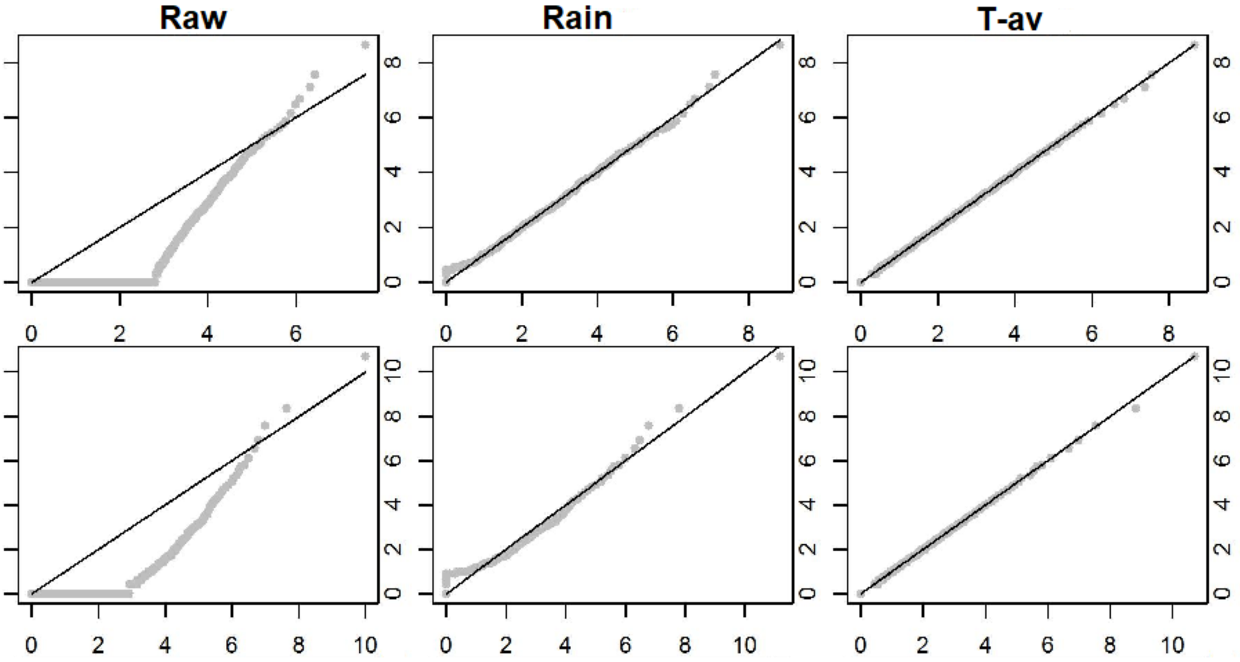

Figure 36: Kenya bias corrected.

Table 15: List of climate stations across Limpopo.

Station	Latitude	Longitude	Altitude
Thohoyandou	-22.97	30.50	600
Polokwane	-23.87	29.45	1300
Levubu	-23.09	30.29	650
Oudestad	-25.18	29.34	944
Giyani	-23.32	30.68	455
Mara	-23.14	29.56	894
Phalaborwa	-23.93	31.15	432

Table 16: List of TAHMO Stations across Kanya.

Station Name	Station code	Latitude	Longitude	Altitude
Lela Primary School	TA00001	-0.18	34.89	1156
Koyoo Secondary School	TA00018	-0.58	34.61	847
Osodo Secondary School	TA00019	-0.75	34.35	546
Woodlands 2000 Trust	TA00020	-1.65	36.86	750
Kipsombe Secondary School	TA00021	0.76	35.17	2725
Bubayi-Saboti Farm	TA00022	0.91	34.92	1794
Dwa Estate	TA00023	-2.39	38.01	884
Mang'u High School	TA00024	-1.07	37.04	1600
Kenya Meteorological Department	TA00025	-1.13496	36.76887	1795

4.2.3. Rainfall Extreme Indices

The present study selected and analyzed two extreme rainfall indices from the climate indices developed by the Expert Team on Climate Change Detection and indices (ETCCDI). The two-rainfall extremes considered in this study were Consecutive Dry Days (CDD) and Simple Daily Intensity Index (SDII) for Limpopo Province and Vhembe District Municipality (VDM). The CCD and SDII were calculated using http://etccdi.pacificclimate.org/list_27_indices.shtml where CCD is defined as maximum number of consecutive days with precipitation < 1 mm. Conversely, SDII is defined as total precipitation divided by the number of wet days (Peterson, 2005).

According to the ETCCDI $\mathrm{SDII} = \frac{\sum_{i=1}^{n} P_i}{N}$ where: Let P_i be the daily rainfall amount on wet days (i.e. days with ≥ 1 mm of rain), N is the number of wet days and n is the total number of days in period. The SDII shows how intense the rainfall is on days when it rains, the higher the SDII values indicate the more rainfall events on day when it rains (Peterson, 2005).

On the other hand, CCD is used to examine dry spell duration, where: CCD = max (number of consecutive days where $P_i < 1$mm). P_i is the daily rainfall, the higher the CCD the longer the dry period (Peterson, 2005).

4.3. RESULTS BASED ON CLIMATE MODELS

4.3.1. Projected Temperature and Rainfall in Limpopo, Vhembe District Municipality (VDM)

Figure 37 – 38 demonstrate projected changes in annual temperature (^{o}C) for both RCP 4.5 and RCP 8.5. for the Limpopo Province and VDM. A noticeable increase in temperature is observed for both scenarios, with an increase between 1º C – 1.5º C for near future (2036 – 2065) under RCP 4.5 moderate scenario. Meanwhile for RCP 8.5 where no significant action is taken to curb greenhouse gas emissions, the eastern parts of VDM are observed to have an increase of 2º C while the western parts the increase in temperature is observed to be 3º C. For far future temperature increases are intensified for both scenarios.

Rainfall is a variable parameter, it has pronounced spatio-temporal variability and the existing numerical weather prediction models are not able to capture the variabilities. In other words, the various numerical weather prediction models do not converge due to inherent uncertainties. The projected annual total rainfall changes for Limpopo Province and VDM (Figure 39 – 40) respectively show a decrease in rainfall for both the RCP scenarios. In the near future the decrease is observed particularly at the center parts of the VDM at 5 – 10%, while Vhembe, Mopani, and Sekhukhune are projected to experience decreases, though less severe. By the far-future period, these trends are expected to intensify, with the most pronounced to be over 10 – 20%. The western parts of Limpopo drying more that the eastern regions. The decrease in rainfall is strengthened in the far future and covers the whole VDM, especially under the no mitigation scenario (RCP 8.5).

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The projected temperature and rainfall in VDM raise a huge concern because the community rely mostly on rainfed agriculture. With increasing temperatures evapotranspiration rate may increase and this will have negative impact on water resources and availability. Constraints on water resources may have implications for agriculture and food security. Moreover, these changes may affect the use of renewable energy such as hydropower.

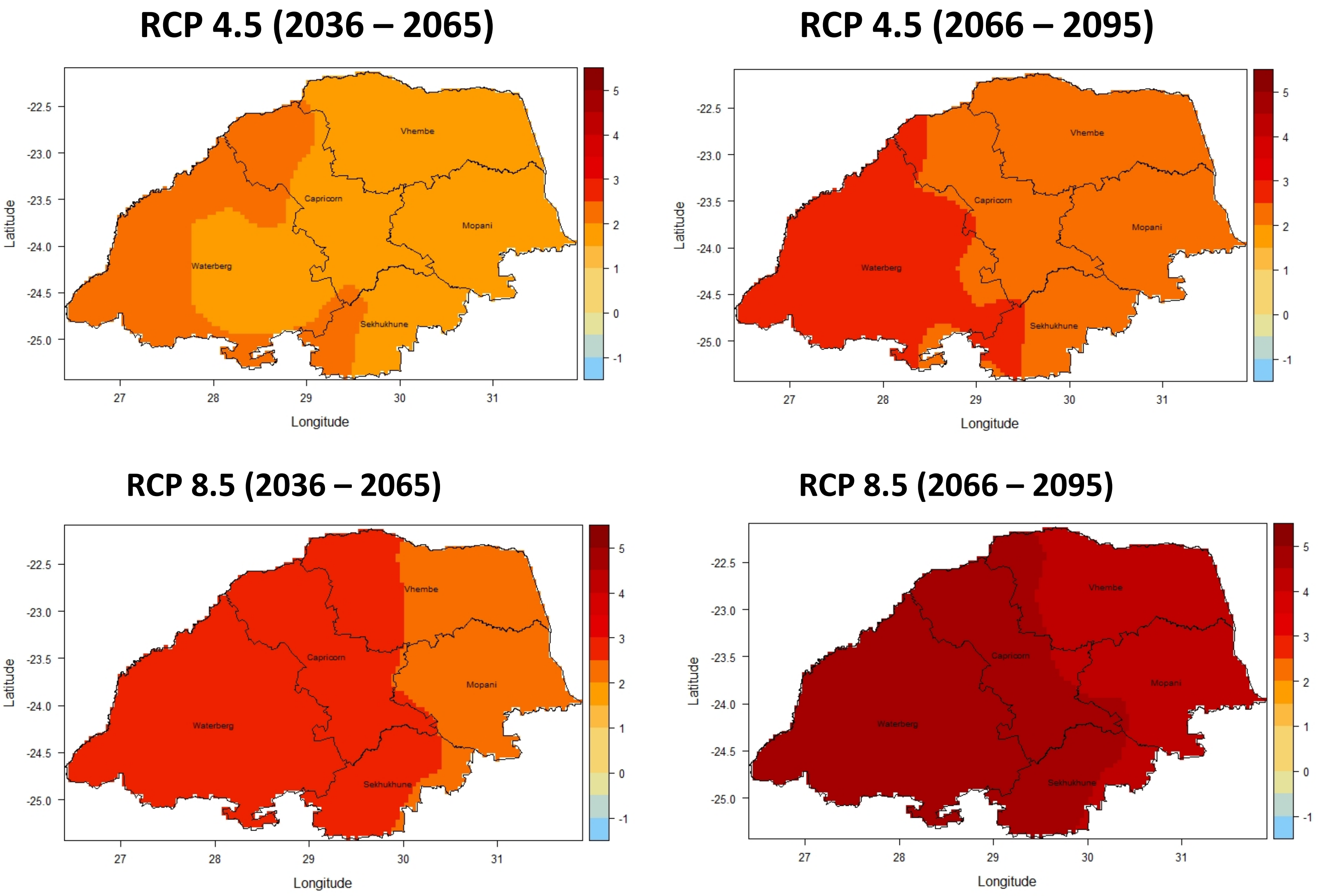

Figure 37: Projected Changes in Annual Surface Temperature (^{0}C) in Limpopo.

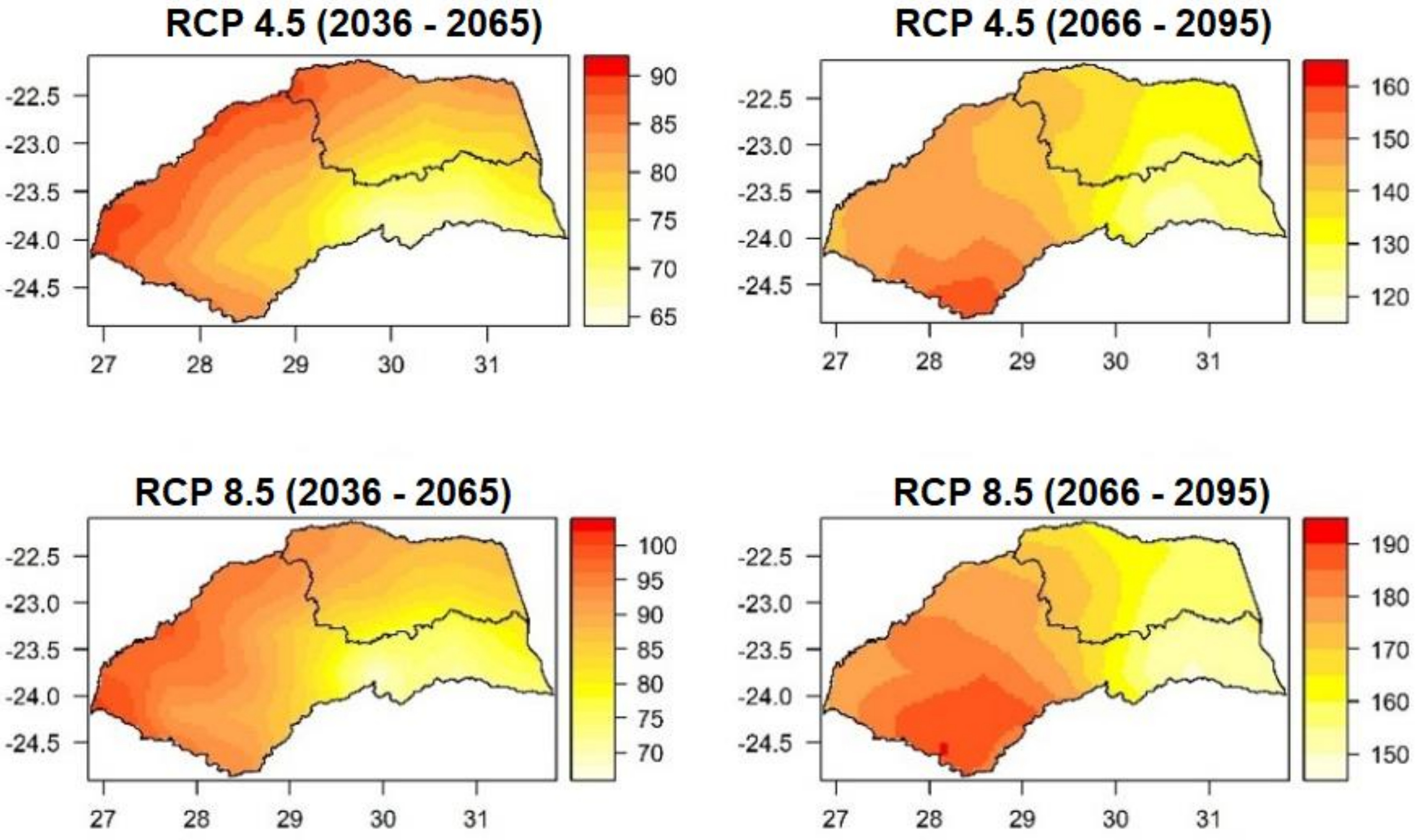

Figure 38: Projected Annual Surface Temperature (^{0}C) in Vhembe District Municipality (x-axis latitude and y-axis longitude).

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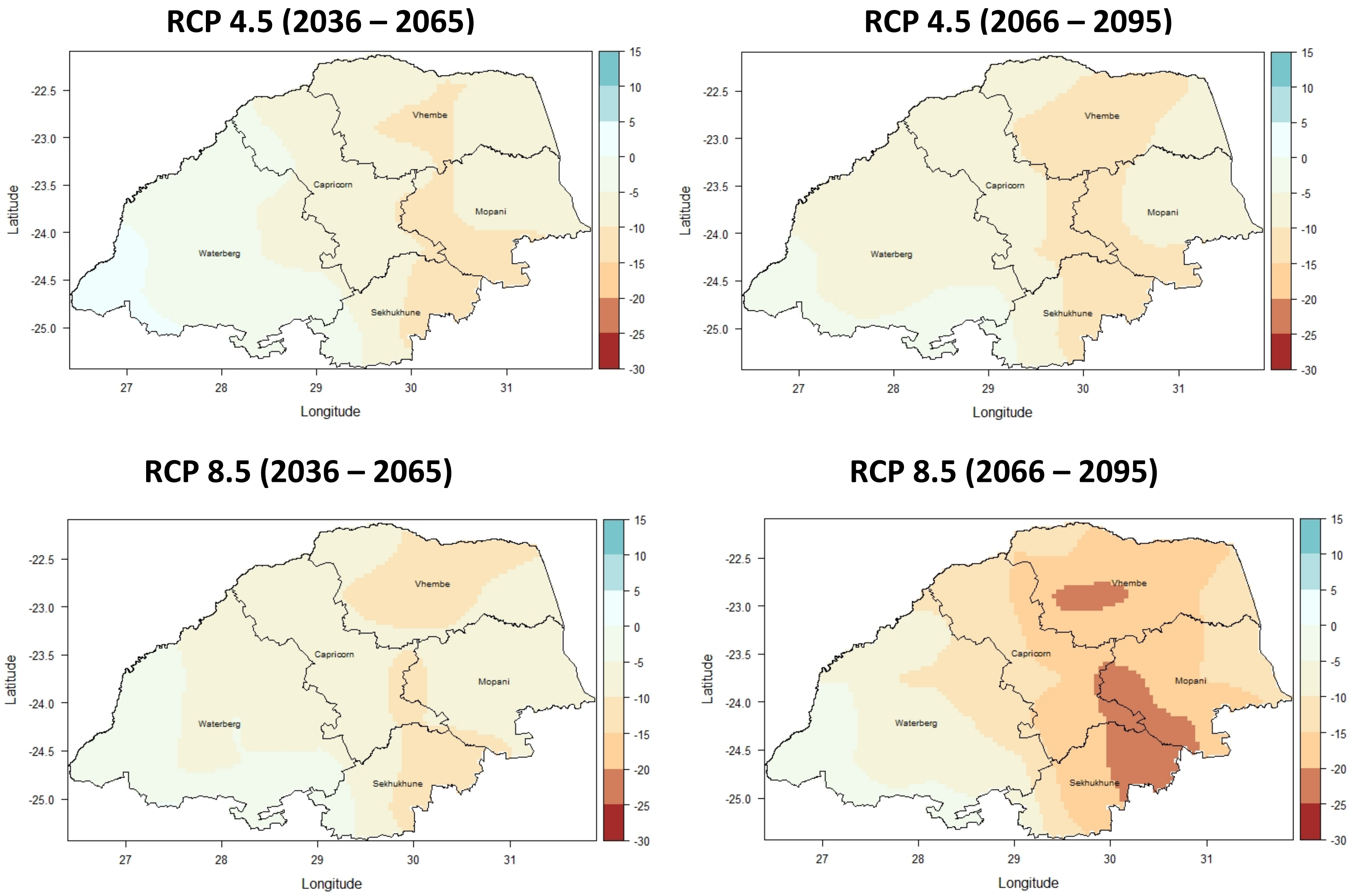


RCP 4.5 (2036 – 2065)

RCP 4.5 (2066 – 2095)

RCP 8.5 (2036 – 2065)

RCP 8.5 (2066 – 2095)

Figure 39: Projected Annual Total Rainfall Change (%) in Limpopo.

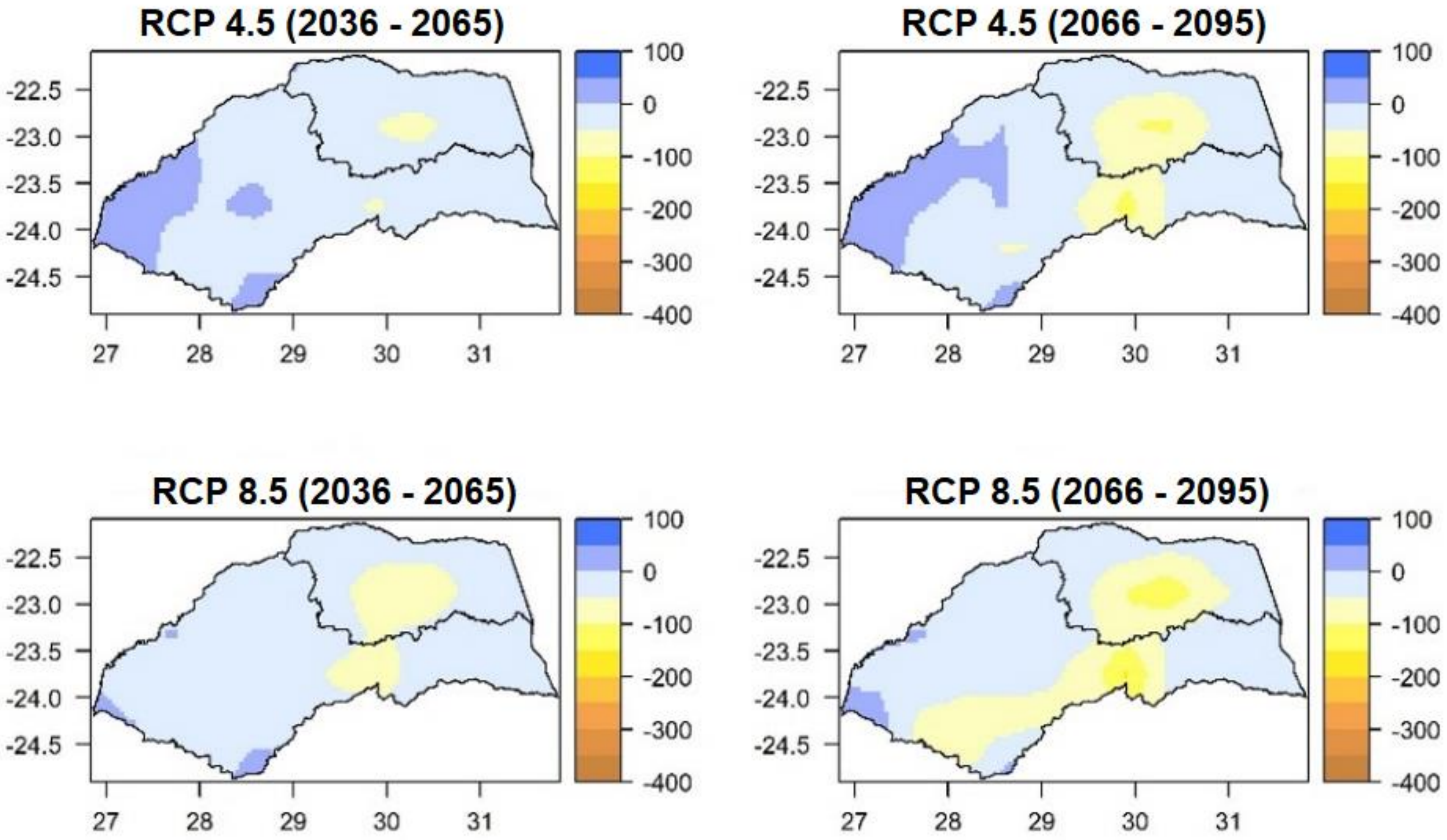


Figure 40: Projected Annual Total Rainfall Change (%) referenced to 1975 – 2005 in Vhembe District Municipality (x-axis latitude and y-axis longitude).

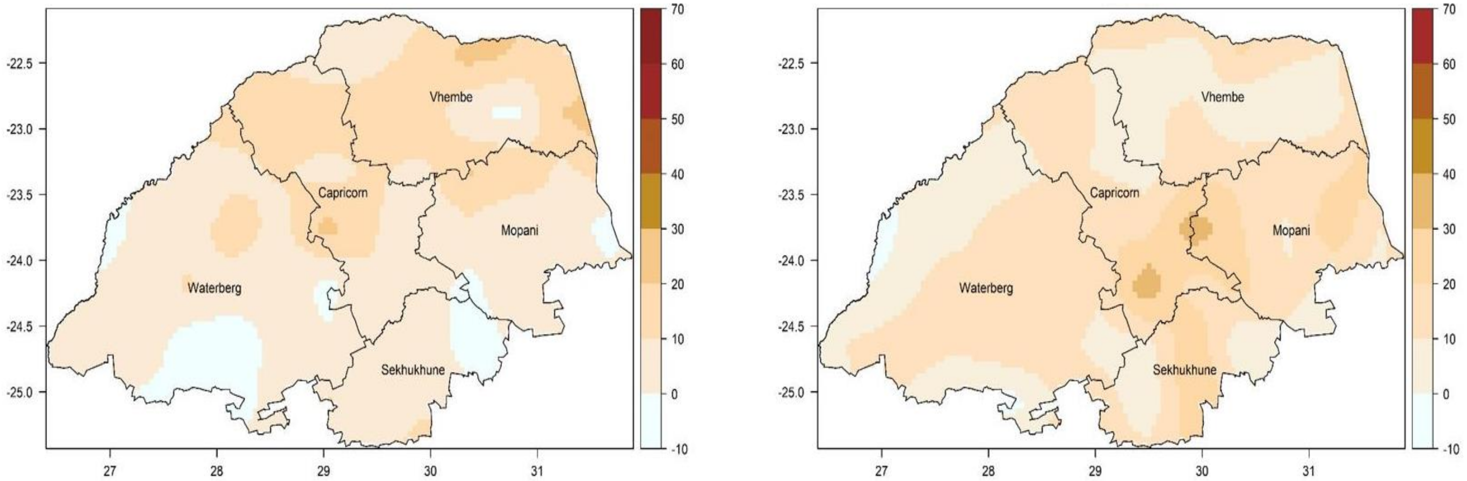
Analysis of Consecutive Dry Days (CDD) and Simple Daily Intensity Index (SDII) for the Limpopo province and VDM was considered. The calculation of the two extreme indices followed was from http://etccdi.pacificclimate.org/list_27_indices.shtml where CCD is defined as maximum number of consecutive days with precipitation < 1 mm. Conversely, SDII is defined as total precipitation divided by the number of wet days. The CDD and SDII are especially significant because they offer complementary insights on precipitation-related climate extremes, which are essential for understanding droughts, managing water resources and agricultural impacts (Hottenstein et al., 2014). The projected annual total rainfall changes in the study site showed that the region is prone to both end of the extreme tails (droughts and floods), thus CDD and SDII were the two main extreme indices of choice in the present study. Moreover, the CDD and SDII are more universally applicable and robust due to their broad applicability, direct connection to climate impacts and simplicity of computation. The CDD illustrates the duration of dry spells which is critical for monitoring drought conditions, assessing agricultural vulnerability and assessing hydrological stress. Meanwhile, SDII gives insight to the intensity of rainfall events, which is a key factor in understanding flood risks, runoff and erosion potential.

The projected CCD under RCP 4.5 in the near- future is observed to increase by maximum between 20 to 30 days in the centre of VDM. On the other hand, in the far future the increase of the same magnitude is observed in the western part of the district. For the business-as-usual scenarios (no mitigation) near future period the increase in the CDD is observed in northern and southern parts of the VDM while far future the increase in CDD has intensified with magnitude of over 40 days and covering the whole region of VDM. The CDD is shown in Figure 41 and Figure 42 for Limpopo Province and VDM respectively.

The SDII shown in Figure 43 – 44 for the Limpopo Province and VDM illustrate a variability across the scenarios and periods. Some areas in the VDM are to experience increased SDII, while some areas will experience a decrease in SDII. The signals of the extreme indices considered in this study demonstrate that VDM is susceptible to both end tails of extreme which are indicative of floods and drought conditions. The changes in climate will have an impact on the country's economy, water security, food security, energy security and health, among others.

RCP 4.5 (2036 – 2065)

RCP 8.5 (2036 – 2065)



RCP 4.5 (2066 – 2095)

RCP 8.5 (2066 -2095)

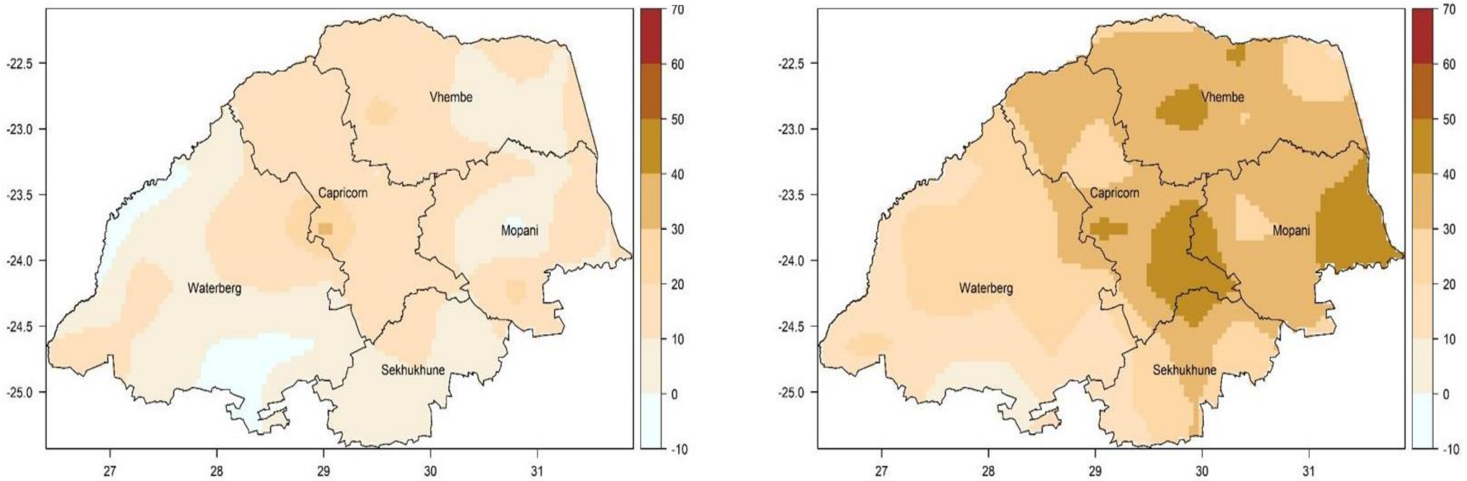


Figure 41: Projected Consecutive Dry Days (mm) in Limpopo (x-axis latitude and y-axis longitude).

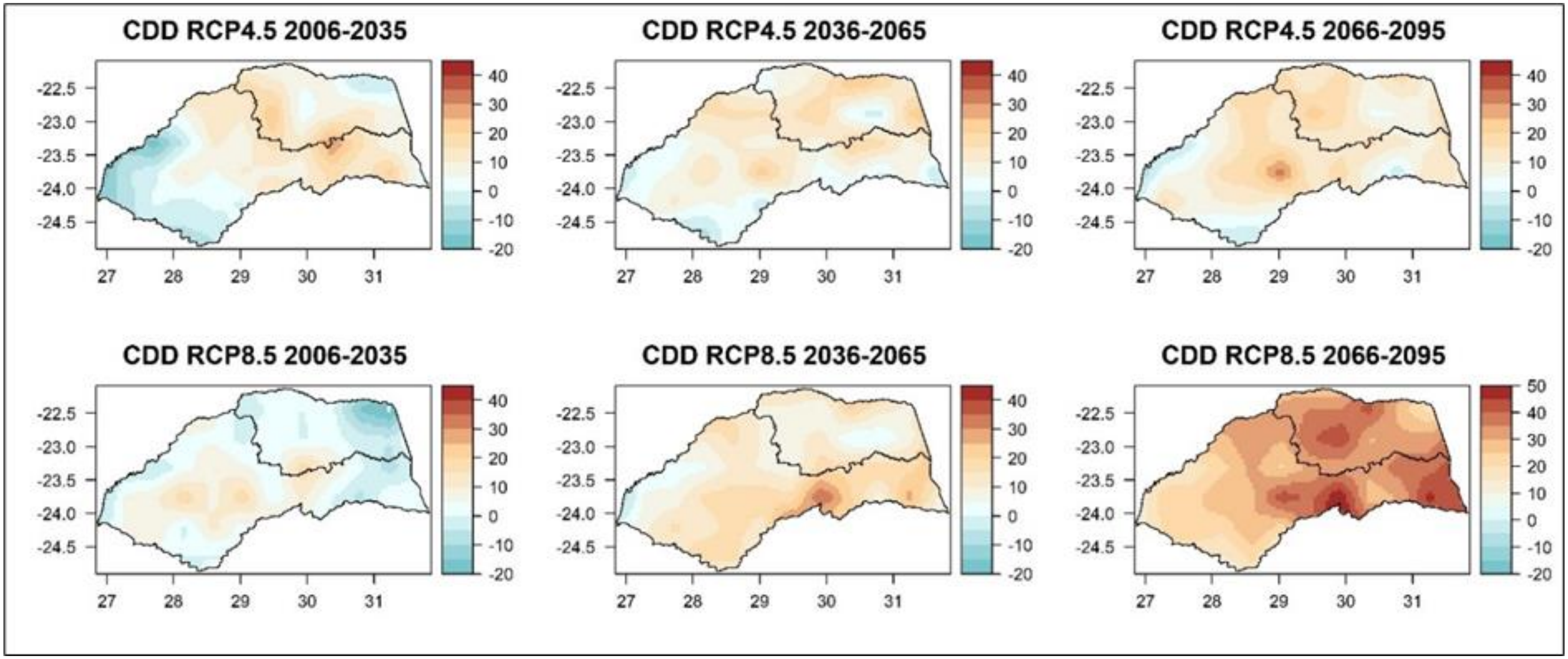
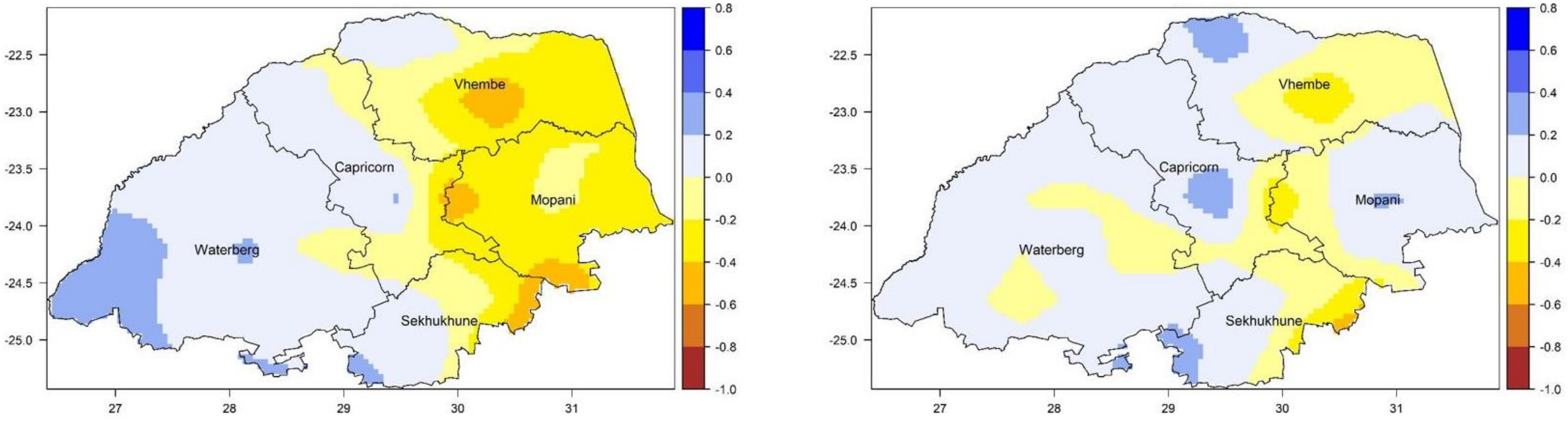
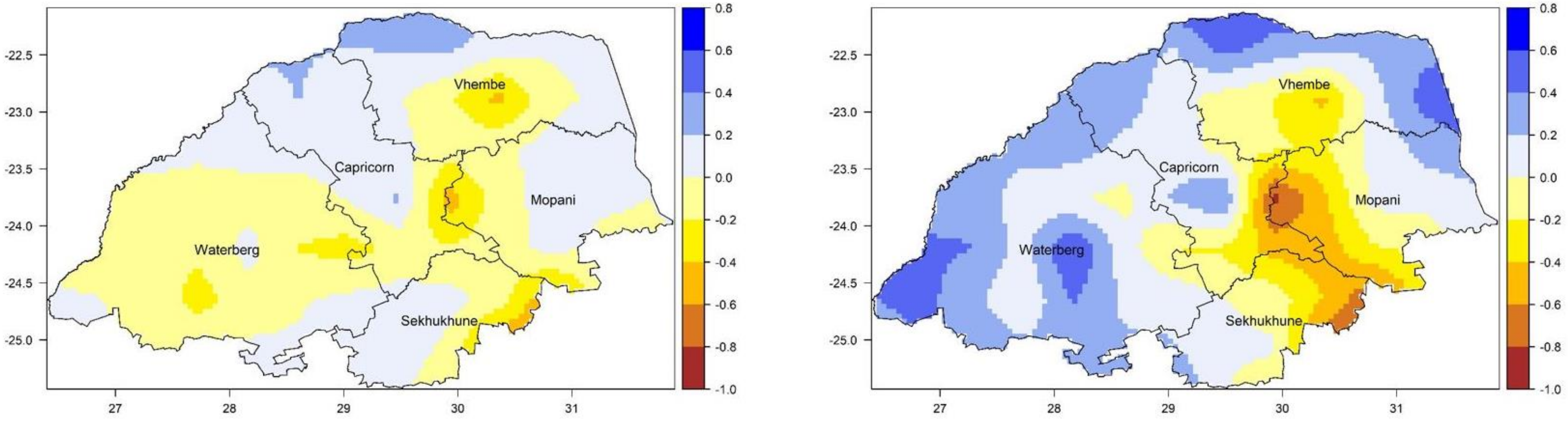


Figure 42: Projected Consecutive Dry Days (mm) referenced to 1975 – 2005 in Vhembe District Municipality (x-axis latitude and y-axis longitude).


RCP 4.5 (2036 – 2065)

RCP 8.5 (2036 – 2065)


RCP 4.5 (2066 – 2095)

RCP 8.5 (2066 -2095)

Figure 43: Projected Simple Daily Intensity Index (mm/day) for Limpopo (x-axis latitude and y-axis longitude).

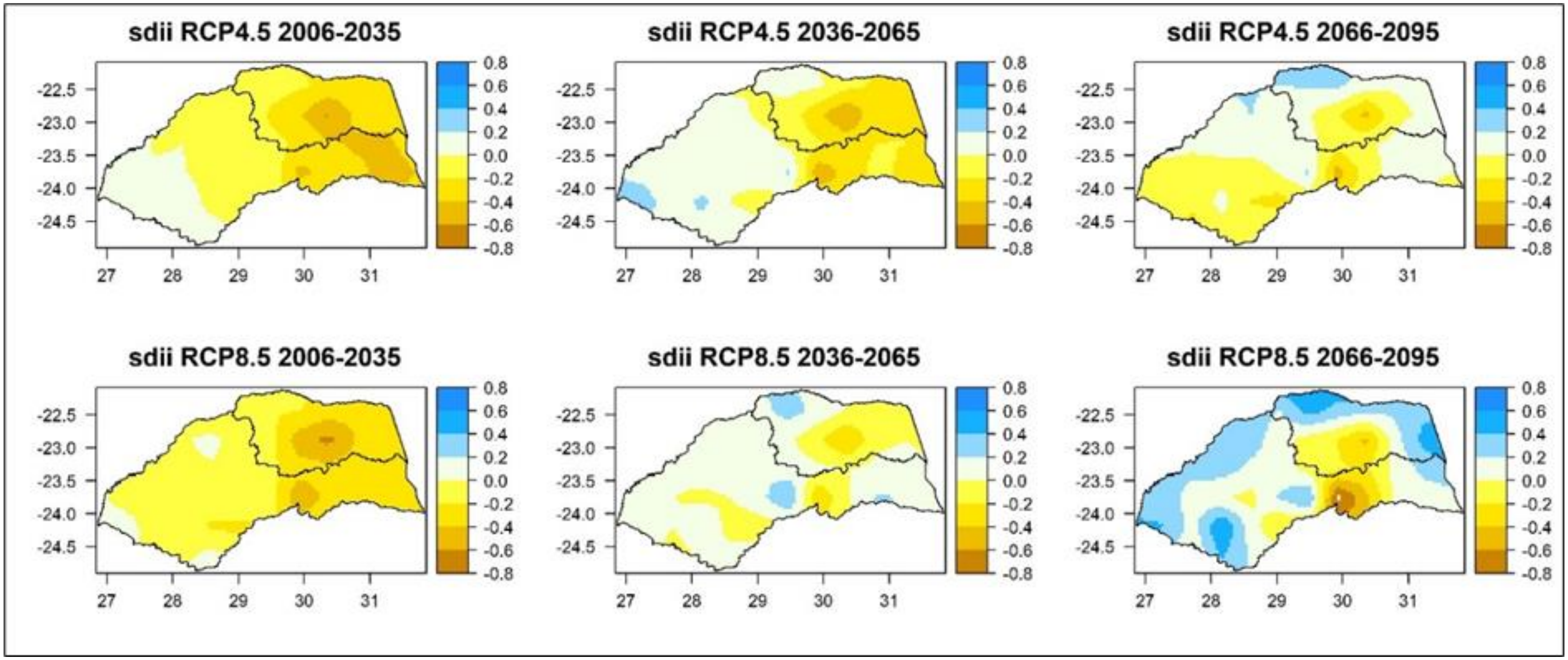
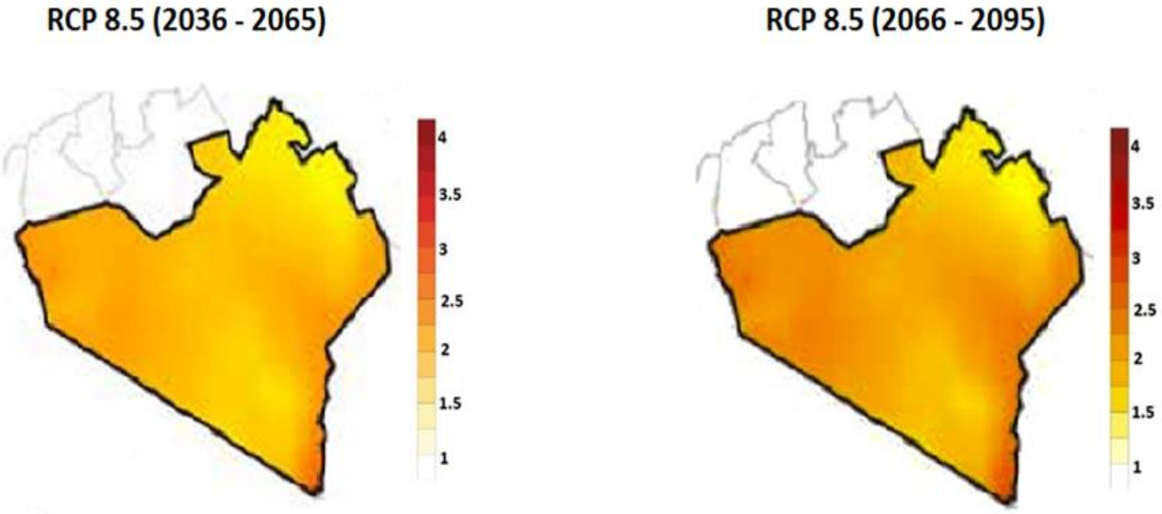


Figure 44: Projected Simple Daily Intensity Index (mm/day) referenced to 1975 – 2005 for Vhembe District Municipality (x-axis latitude and y-axis longitude).

4.3.2. Projected Temperature and Rainfall in Narok County

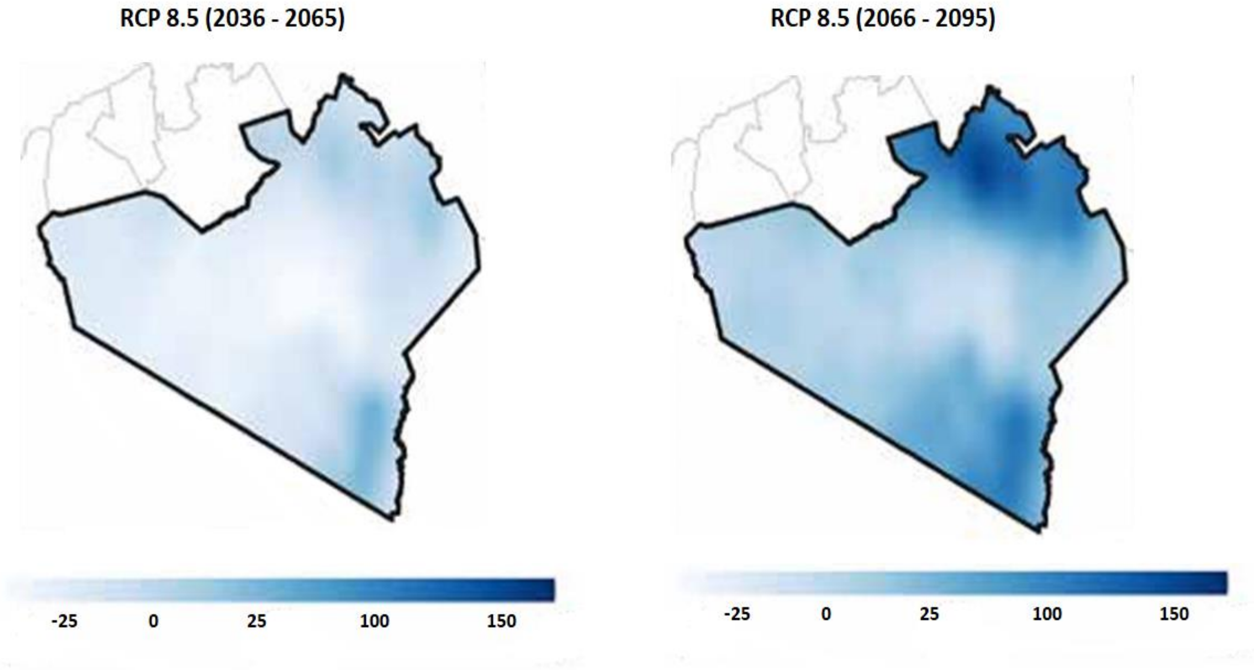
Figure 45 shows projected changes annual surface temperature (ºC) for the worst-case scenario, no mitigation (RCP 8.5) for the near-future 2036 – 2065 and far-future 2066 – 2095 periods. Clearly illustrated is that in the near future period the warming across Narok County varies, with northern parts warming at over 1.5ºC and the rest of the country between 1º C to 1.5º C. On the other hand, in the far-future the increase in temperature is intensified. Most of Narok County is projected to have increased temperatures of over 2º C. The findings are in agreement with the Kenya Climate profile which was conducted in 2020 where temperature trends were projected to continue rise by over 1.5º C the year 2050 and over 3º C by the end of the century. The projected increase in temperature will have significant implications for health, agriculture, water and energy sectors.

Figure 46 illustrates the annual total rainfall change (%) in Narok County. Unfortunately, rainfall has a high spatio-temporal variability which cannot be captured by the models due to the intrinsic uncertainties. According to Marigi (2017), climate change has caused Narok County rainfall season to become more unpredictable. In Figure 46 we observed that for the near future some areas will have increased rainfall (south of Narok), while a big part of Narok no change in rainfall is observed. Meanwhile, for the far future, a clear sign of an increase in rainfall is observed for most parts of Narok County. In this regard extreme rainfall events are expected to increase frequency, duration and intensity, which will lead to high flooding in Kenya. In April 2024 various media reported extreme rainfall, and floods have been impacting larger areas in Kenya. Since this was countrywide, the reports attributed the flooding event to changing climate.


RCP 8.5 (2036 - 2065)

RCP 8.5 (2066 - 2095)

Figure 45: Annual Surface Temperature Change Projections in Narok County, Kenya.


RCP 8.5 (2036 - 2065)

RCP 8.5 (2066 - 2095)

Figure 46: Annual Total Rainfall Change Projections Narok County, Kenya.

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4.4. RESULTS BASED ON STAKEHOLDER ENGAGEMENT

4..4.1. Modeling Framework

To capture the views and opinions of the communities in Vhembe District Municipality and Narok County we formulated a direct modeling framework between water, energy and food resources and climate to understand the present and future impacts of climate change as perceived by the communities in the study sites. This SEM framework has already been described in Chapter 2 and Chapter 3. Figure 47 shows the modeling framework with independent variables (IV - water, energy and food) and dependent variables (DV – future climate). The extent of the investigation was limited to basic understanding of how the respondents perceived what will be the impact of climate change on the availability and accessibility of WEF resources.

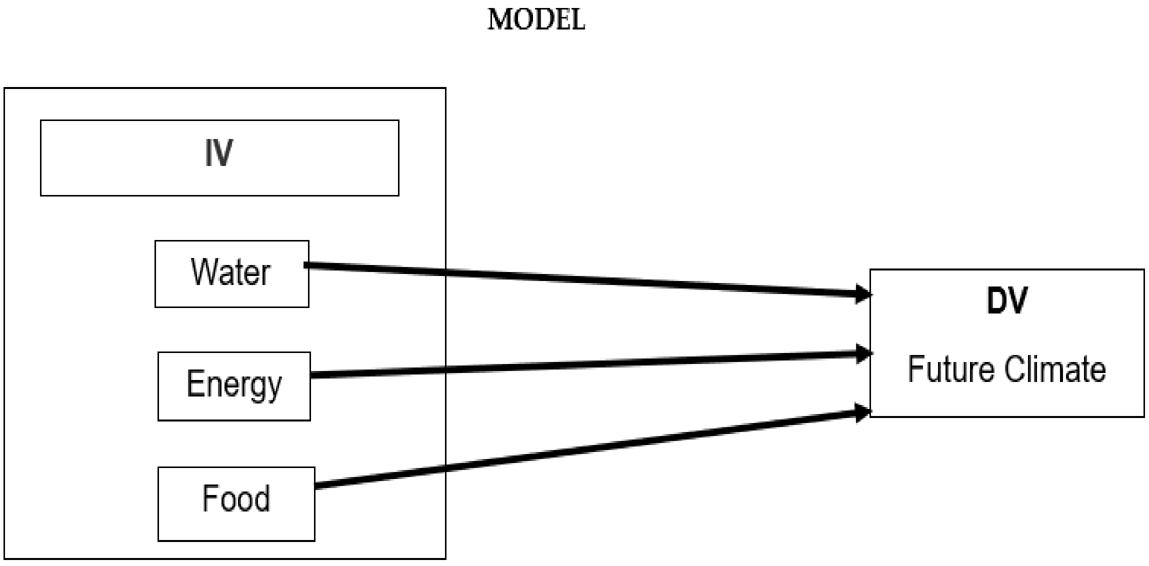

Figure 47: Community perception modeling framework.

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4.4.2. Results of the Framework

Relationship 1 is water and climate for original model (top) and bootstrapped model (bottom) is shown Figure 48. The bootstrapped model indicates if the relationship is significant or non-significant where a 5% confidence interval for the direct path is calculated (Zwane et al., 2024). Water has two measured variables, while climate has three measured variables. Clearly illustrated in Figure 48 is that water has a negative significant link to climate with coefficient of β = -0.177** (asterisk indicates significant level). A measure of reliability to show confidence of the model accuracy indicated by Alpha, rhoC and rhoA to exceed threshold of 0.7 (Zwane et al., 2024) is shown in Figure 49. Climate indicates more reliability for relationship 1, illustrated in Figure 49.

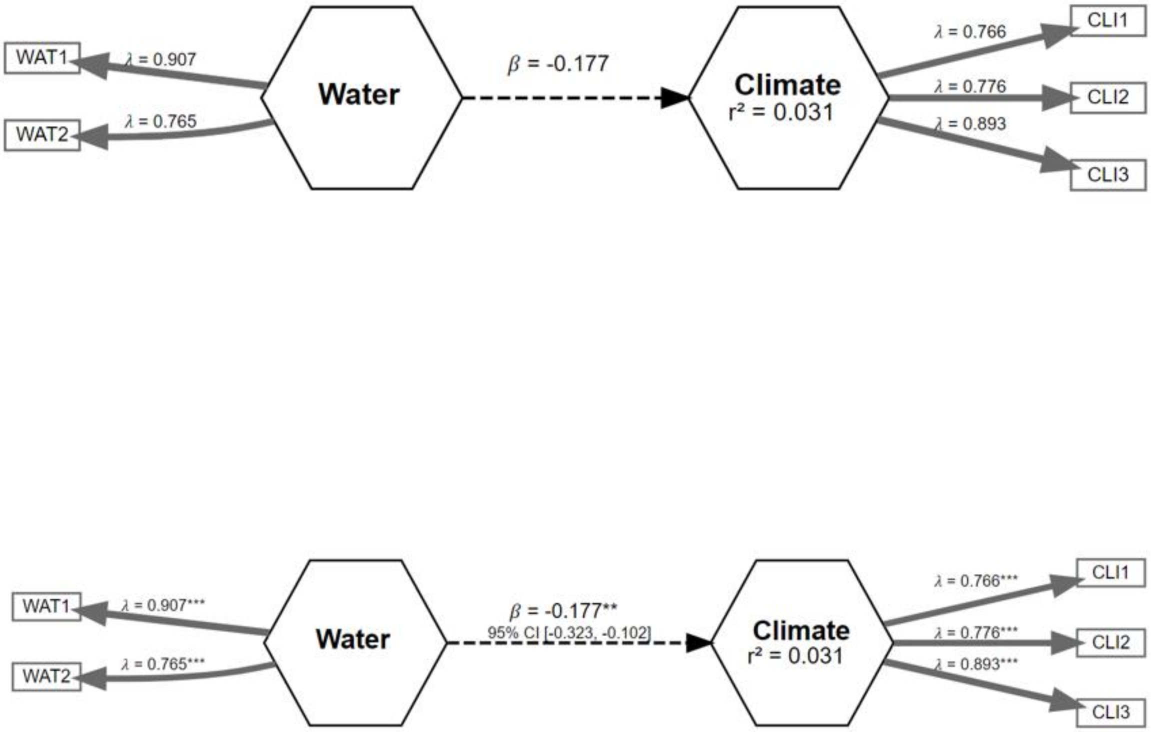

Figure 48: Relationship 1 for both sites - Water and Climate model (top) and the bootstrapped model (bottom). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

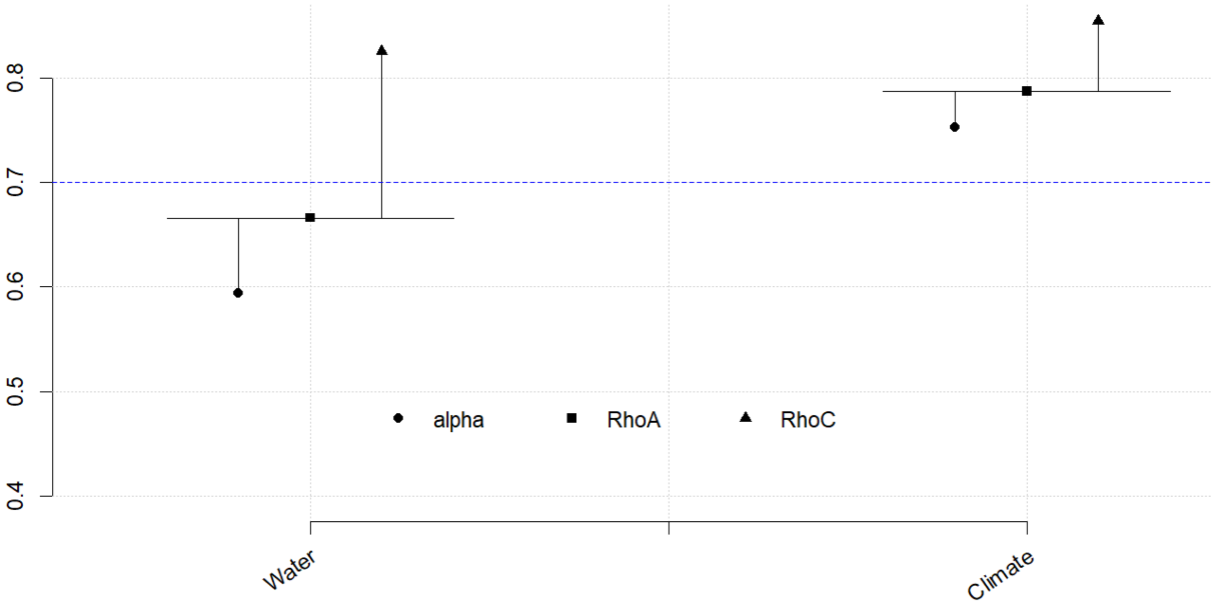

Figure 49: Reliability graph for relationship 1 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

Figure 50 indicates relationship 2 for energy and climate for original model (top) and bootstrapped model (bottom). Similarly to relationship 1, relationship 2 indicates that energy has significant indirect effect to climate with coefficients β = -0.182**. For relationship 2 (Figure 51) climate shows more reliability compared to energy, with only rhoC exceeding 0.7. Furthermore, we explored relationships 3 (food and climate) in Figure 52. Like water and energy, food also depicts a significant indirect negative impact on climate with coefficient of 0.248**. The reliability graph in Figure 53 shows that climate is more reliable.

The results of the framework for the three relationships in line with the perceptions of the communities from both the study sites illustrate that the WEF resources in the study sites have a significant indirect impact on future climate. According to Zwane et al (2024), The negative impacts influencing the three sectors mostly manifest from the increased stress and scarcities of the WEF resources, complimented by a high rate of population growth, variations in resource consumption, including land-use patterns, and exacerbated by climate change.

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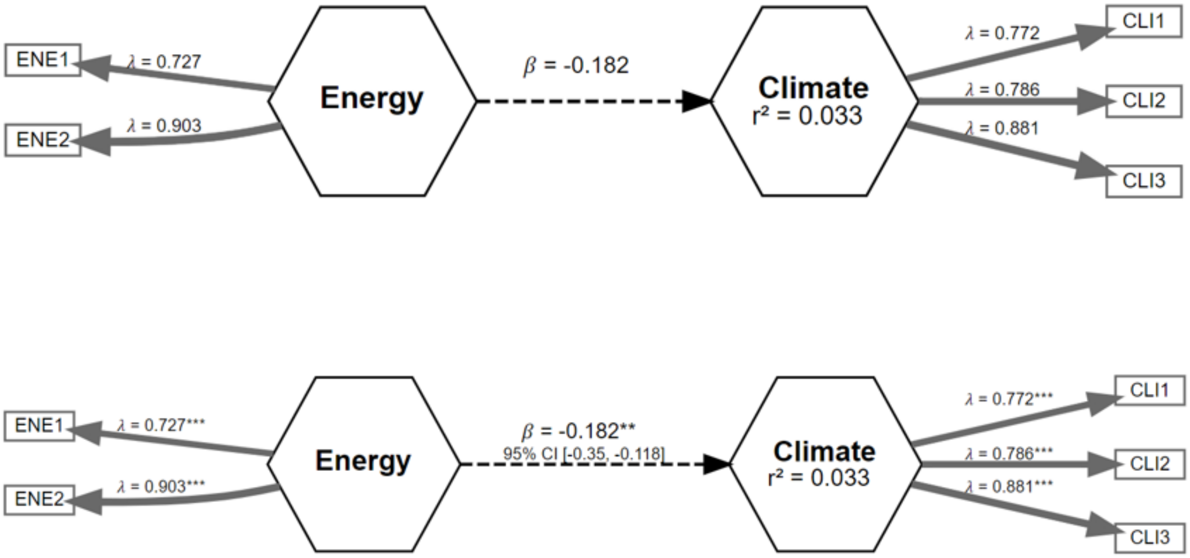

Figure 50: Relationship 2 for both sites - Energy and Climate model (top) and the bootstrapped model (bottom). Asterisk is the significance level. * p < 0.05 ** p < 0.01 *** p < 0.001.

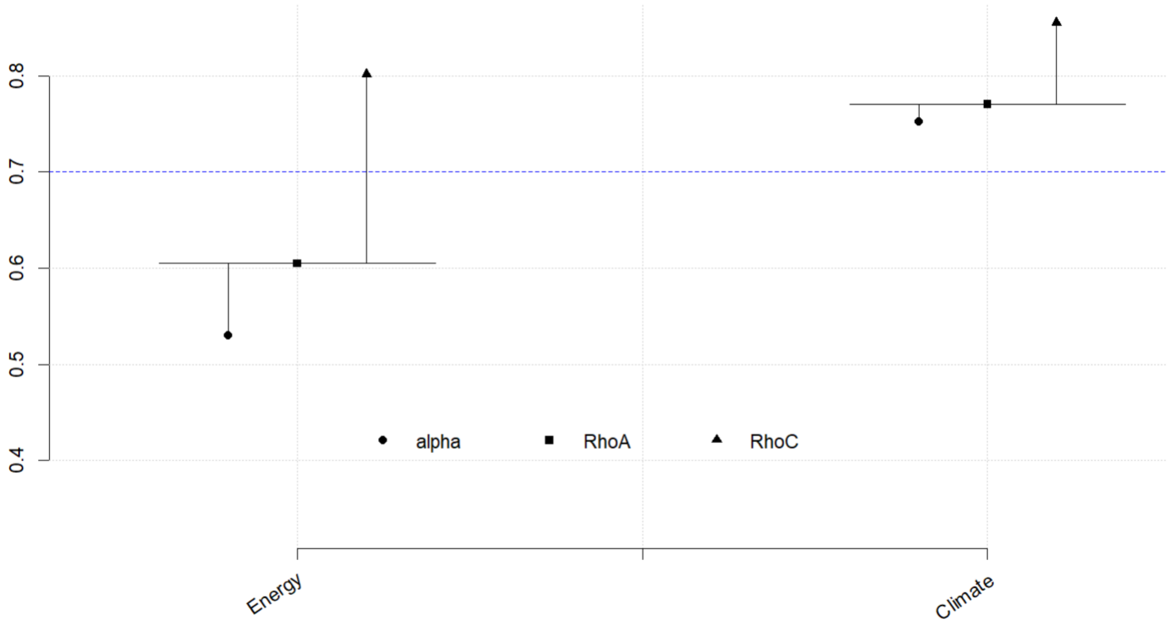

Figure 51: Reliability graph for relationship 2 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

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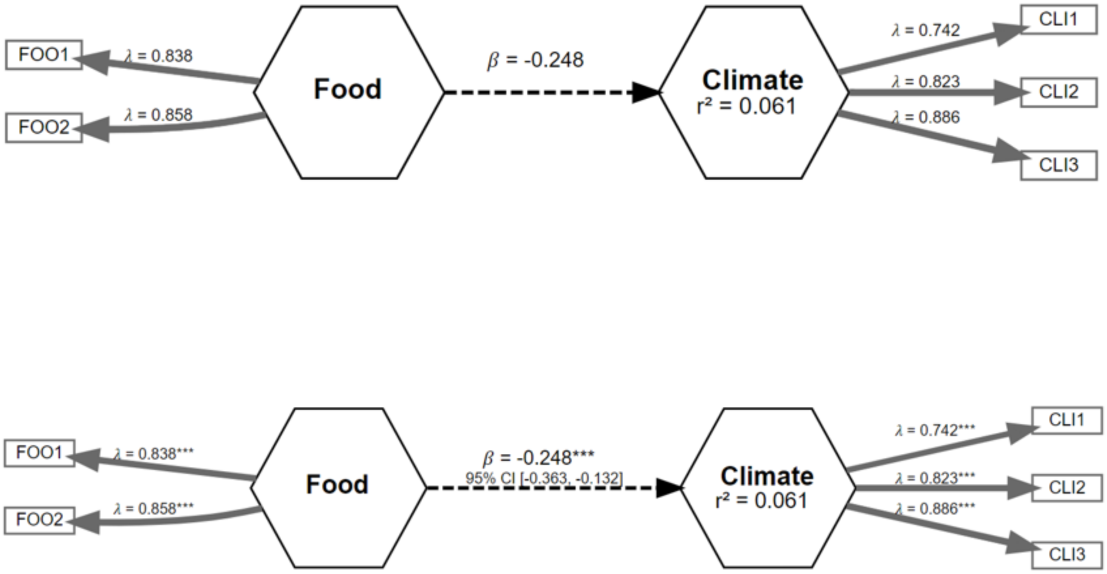

Figure 52: Relationship 3 for both sites - Food and Climate model (top) and the bootstrapped model (bottom). Asterisk is the significance level. * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

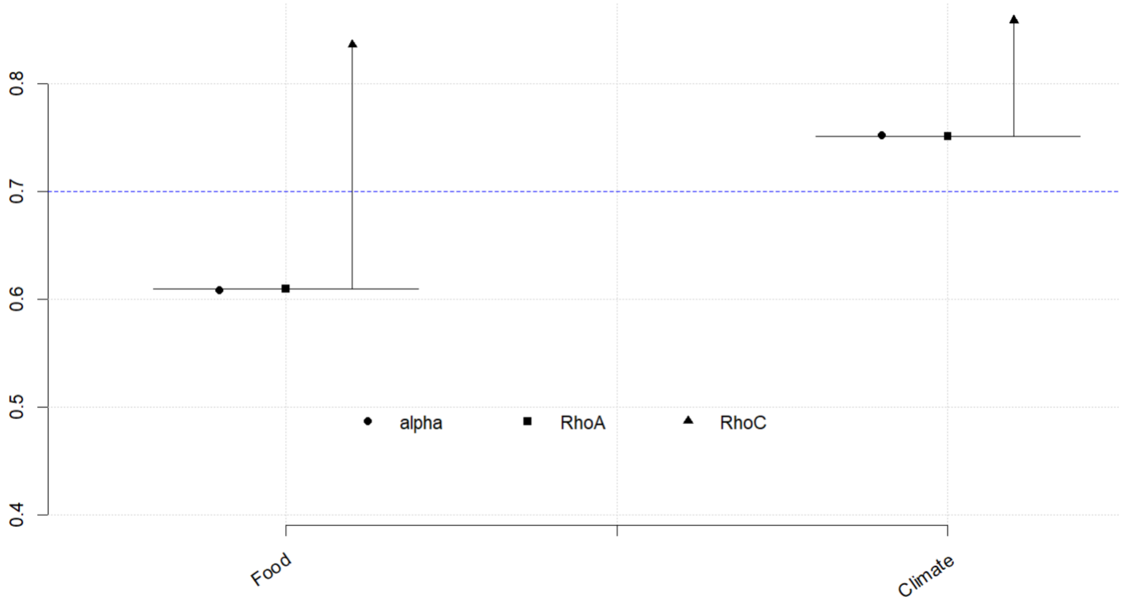

Figure 53: Reliability graph for relationship 3 – both sites (the dash line is the 0.7 threshold, and the y-axis are the reliability values).

4.5. DISCUSSION AND CONCLUSION

The findings in chapter two demonstrated an imbalance in resource management in the Vhembe District Municipality and Narok County. Observed from the systematic map (Figure 11), is that it is challenging to guarantee the availability and security of all three resources in the study sites due to the increased demand for water, food and energy. The projected climate change in the study sites is associated with extreme events such as droughts and floods as well as increased temperatures. According to Mpandeli et al (2018), by the year 2050 the demand for food and water will increase by 50%, while the global demand for energy would have doubled.

Both VDM and Narok County economy and livelihood depend on rain to be able to provide water, energy and food requirements for the communities. The dependance of the economy on rainfed agriculture in both study sites makes food systems highly sensitive to changing patterns of rainfall. The projected climate will exacerbate the challenges of meeting the WEF needs. The anticipated perturbation in agriculture will affect food availability and accessibility. On the other hand, changes in frequency and intensity of rainfall lead to increased incidence of droughts and floods which have an impact on food production and distribution. Adverse changes in the quantity, quality, and accessibility of water resources would make it more energy-intensive to pump water from farther or deeper depths or to purify water of lower quality, which would increase competition for the limited supply of water resources between the food and energy sectors. In this regard potential modifications in the feedstocks used for renewable energy could have additional effects on the energy system.

This study has considered two sites that have similar socio-economic, environmental and climatic conditions. It was therefore prudent to characterize the present and projected future climatic conditions. Our analysis results point to pronounced hydroclimatic extremes (Botai et al., 2024 and Zwane et al., 2024). The expected frequent hydroclimatic extremes will have profound impacts on climate sensitive sectors, such as water, agriculture, energy, built environment and health. To respond to these hydroclimatic extremes, innovative solutions (e.g., early warning systems) ought to be co-developed and deployed to the communities susceptible to these conditions. In addition, these results have practical implications to policymakers from the perspective of prioritization of future developmental options that the two study regions would consider improving their livelihoods.

The survey results of existing water, energy and food resources in the two study sites demonstrated that the resources are generally constrained. Additionally, the existing interlinkages of the WEF resources are complex and therefore not easily understood. It is against this backdrop that a parsimonious modelling framework has been developed in the present study. The modelling framework considers the interlinkages between the WEF resources as constrained by present and projected climate change proxies. The utility of this framework is that it considers community's views of present and projected climate change impacts. As a result, the community's perspective of climate change impacts is incorporated into the modelling framework. It is opined that the developed framework is robust based on the vital reliability measures, often reported in Structural Equation Modelling (SEM), see for example (Cheung et al., 20204). The modelling framework results illustrate that the present WEF nexus interlinkages will be altered by the projected climate change. This implies that the future interlinkages and trade-offs of the WEF resources would inform developmental policies that will help sustain the community's resilience and therefore sustainable livelihoods.

The novelty of the present study has sort to simply the often-complex WEF nexus modelling framework that is largely theoretical but with little practical localized implications. It is opined that, for the first time, the current study infuses community's perspectives of climate change impacts onto a simple WEF nexus modelling framework based on SEM. This work therefore contributes to the scientific body of knowledge of WEF nexus and systems thinking. In addition, this study has a practical contribution to the WEF nexus resources policy development and implementation.

Several studies (Botai et al., 2024, Zwane et al., 2024, Botai et., 2021 and Mpandeli et al., 2018) have opined that the WEF nexus could be a conceptual framework in support of adaptation and mitigation to climate change because of its cross sectoral approach to resource planning and management. WEF resources are intricately connected, with usage within one sector influencing the use and availability of the other two sectors. This chapter illustrates that both study sites share similar socio-economic and environmental challenges. Future changes in rainfall and temperature will exacerbate the scarcity of WEF resources and increase the vulnerability in both study sites. A well-structured WEF resource management is required in order to increase the resilience of marginalized communities in VDM and Narok County, moreover, adding towards attainment of sustainable development goals (SDG 1, 2, 3, 6, 7 and 13). Furthermore, the results on how climate change would affect the interlinkages of WEF resources from the models and output from fieldwork uncovered that communities need to be consulted. Thus, we advocate that there is a need for government to adjust policies notwithstanding the developmental options.

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CHAPTER FIVE: CONCLUDING REMARKS AND RECOMMENDATIONS

5.1. Conclusion

Climate change coupled with population growth as well as other socio-economic and environmental factors such as land degradation and urbanization are likely to have an impact on water, energy and food resources particularly in vulnerable communities. This study explored two different sites (Narok County and Vhembe District Municipality) that exhibit similar socio-economic, environmental and technological circumstances to highlight the climate change impact on the nexus between water, energy and food resources. In the present study, results showed that the WEF nexus methodology is important for advancing understanding and managing complex relationship between water, energy and food. Several studies internationally and locally have utilized the WEF nexus as conceptualized framework and an analytical tool. One of the problems observed with the implementation of the WEF nexus is to shift from theory to practice. The challenge observed is due to lack of understanding of the linkages between the WEF nexus system, limited reliable models and data necessary to develop and test technologies that can be utilized for translation of WEF nexus from theory to practice.

In this study the results unequivocally showed that there is an imbalance in resource management in Narok County and the Vhembe District Municipality. These findings support those of a study by Botai et al. (2024), which used the WEF nexus framework to evaluate rural livelihoods, health, and wellbeing in Narok County and Vhembe District Municipality. Furthermore, that study also classified both study sites under the lowly sustainable category.

The Structural equation modelling (SEM) utilized on the survey data confirms that climate change significantly impacts WEF resource availability. Using structural equation modelling (SEM) to analyze these relationships is a notable methodological advancement that enhances the study's rigour. In this research we investigated how the WEF nexus can support the transition towards sustainable development. The analysis demonstrated that food positively affects sustainability, while water and energy have negative indirect effects. Furthermore, this research highlighted the importance of sustainable resource management for climate adaptation and contributing to the 2030 UN Sustainable Development Goals (SDGs).

From literature as well as from responses from the participants in this study it was clearly outlined that the study site has scarcity in WEF resources. From the long-term temperature and rainfall analysis we showed that the projected climate in both study site is likely to have an impact on WEF resources thereby accelerating the scarcity of WEF resources and increasing the exposure and vulnerability of the communities in Narok County and Vhembe District Municipality. In this study we successfully quantified and modelled the interlinkages of WEF resources from the supply and demand perspective which is vital for cascading effective calculation of the direct and indirect WEF nexus loops. Moreover, the present study provides recommendations for policy and decision makers in scaling up and implementing the WEF nexus approach.

This study asserts that an integrated approach involving political systems, different stakeholders, and role-players must collaborate to define and derive appropriate trade-offs with the WEF resources value chain, particularly considering the current changing climate, in order to achieve sustainable development within the WEF sectors. Furthermore, it is recommended that integration of the institutions charged with policy making and implementation of WEF-nexus approaches be strengthened. Additionally, it is intended that the study highlights the significance of citizen participation and wide stakeholder engagement in promoting information sharing, bottom-up solutions, and conflict resolution. Owing to the projected hydroclimatic extremes in both study sites, it is averred that a transformative, gender inclusive socio-economic developmental options be adopted in order to ensure that communities in the study sites are sustainably resilient.

5.2. Future work

The present study has established that WEF security is closely related to the sustainability of humans, the environment and the economy. Inadequate supply or access to WEF resources can cause several health issues as a result poor water quality, unhealthy diet and lack of intermittent energy. These effects become more when these variables are combined. It will be beneficial for the future work to investigate the following topics to sustainably improve the livelihoods, human and ecosystems health and wellbeing.

- Development and optimization of sustainable and equitable green and blue economy in Africa
- Integrated early warning multi-level approach into the governance and management of WEF resources in vulnerable communities

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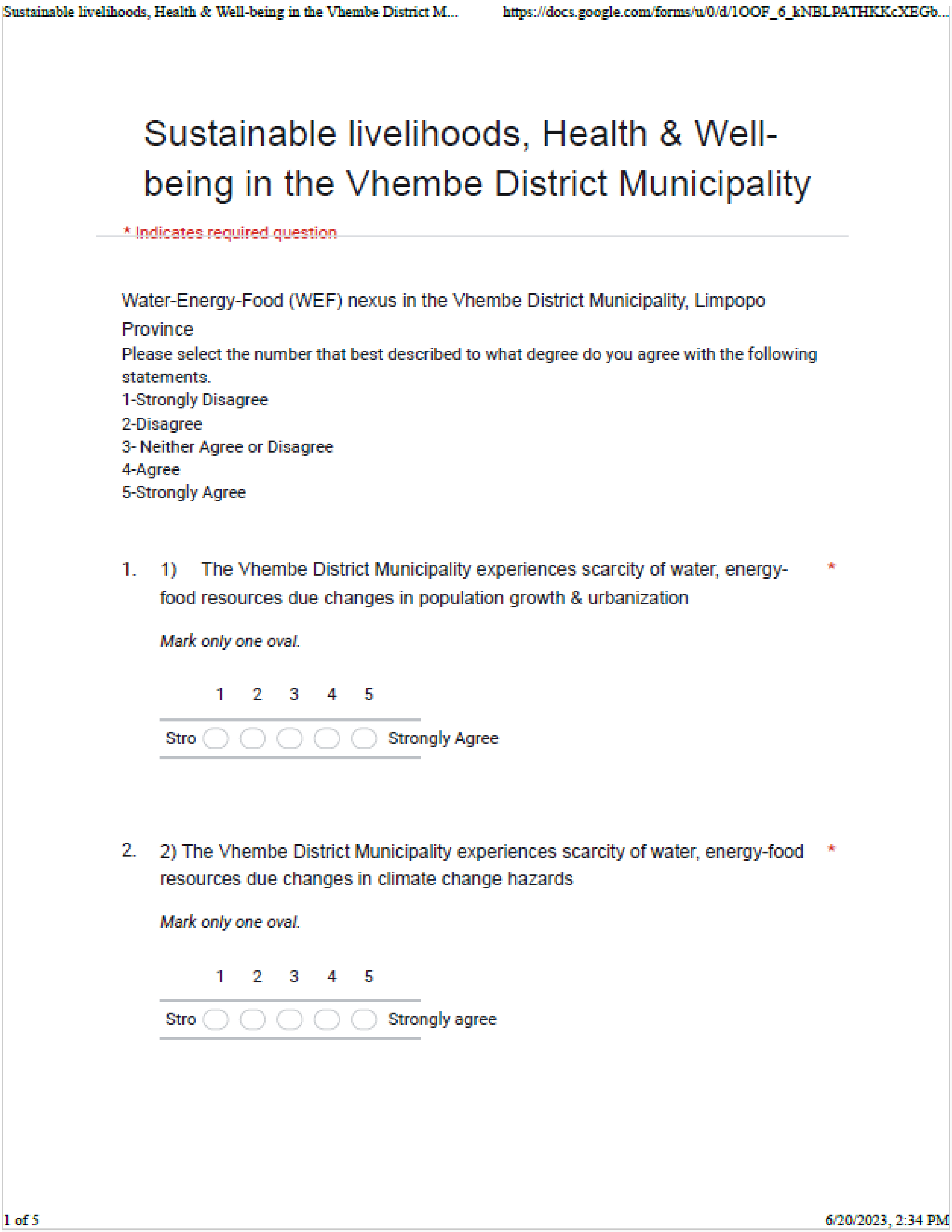
APPENDIX A



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

* Indicates required question

Water-Energy-Food (WEF) nexus in the Vhembe District Municipality, Limpopo Province

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

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

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly Agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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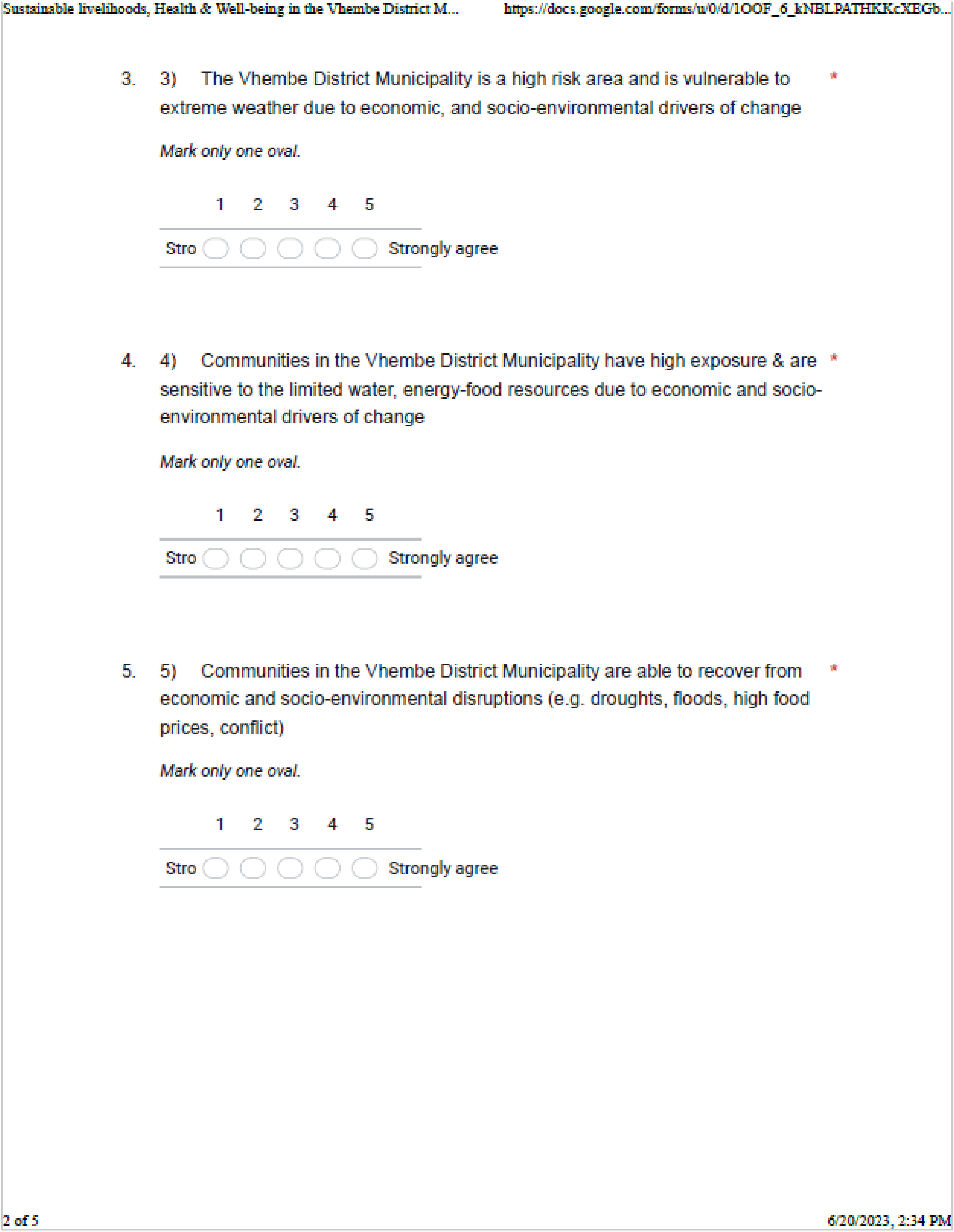

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3. 3) The Vhembe District Municipality is a high risk area and is vulnerable to extreme weather due to economic, and socio-environmental drivers of change *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

5. 5) Communities in the Vhembe District Municipality are able to recover from economic and socio-environmental disruptions (e.g. droughts, floods, high food prices, conflict) *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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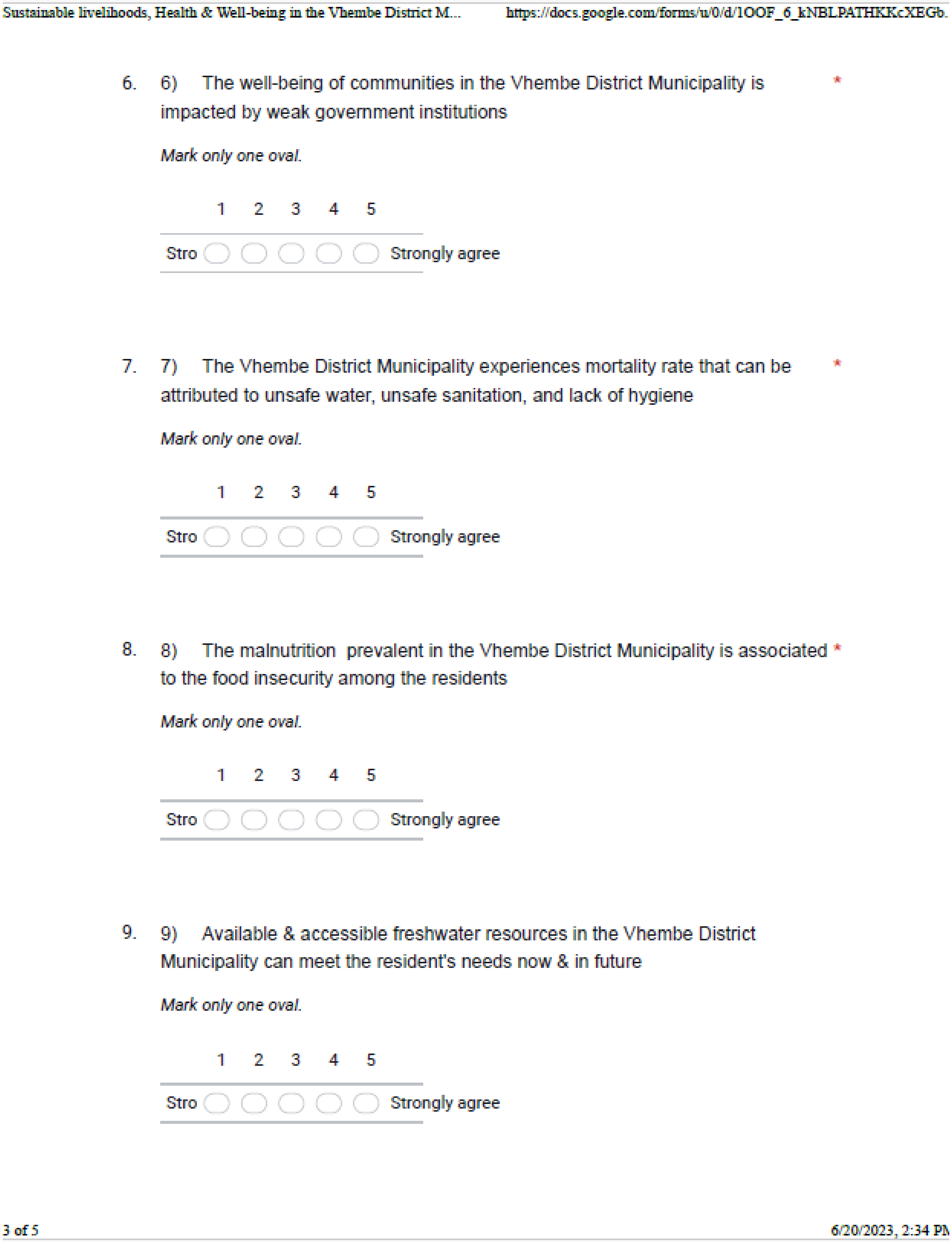

6. 6) The well-being of communities in the Vhembe District Municipality is impacted by weak government institutions *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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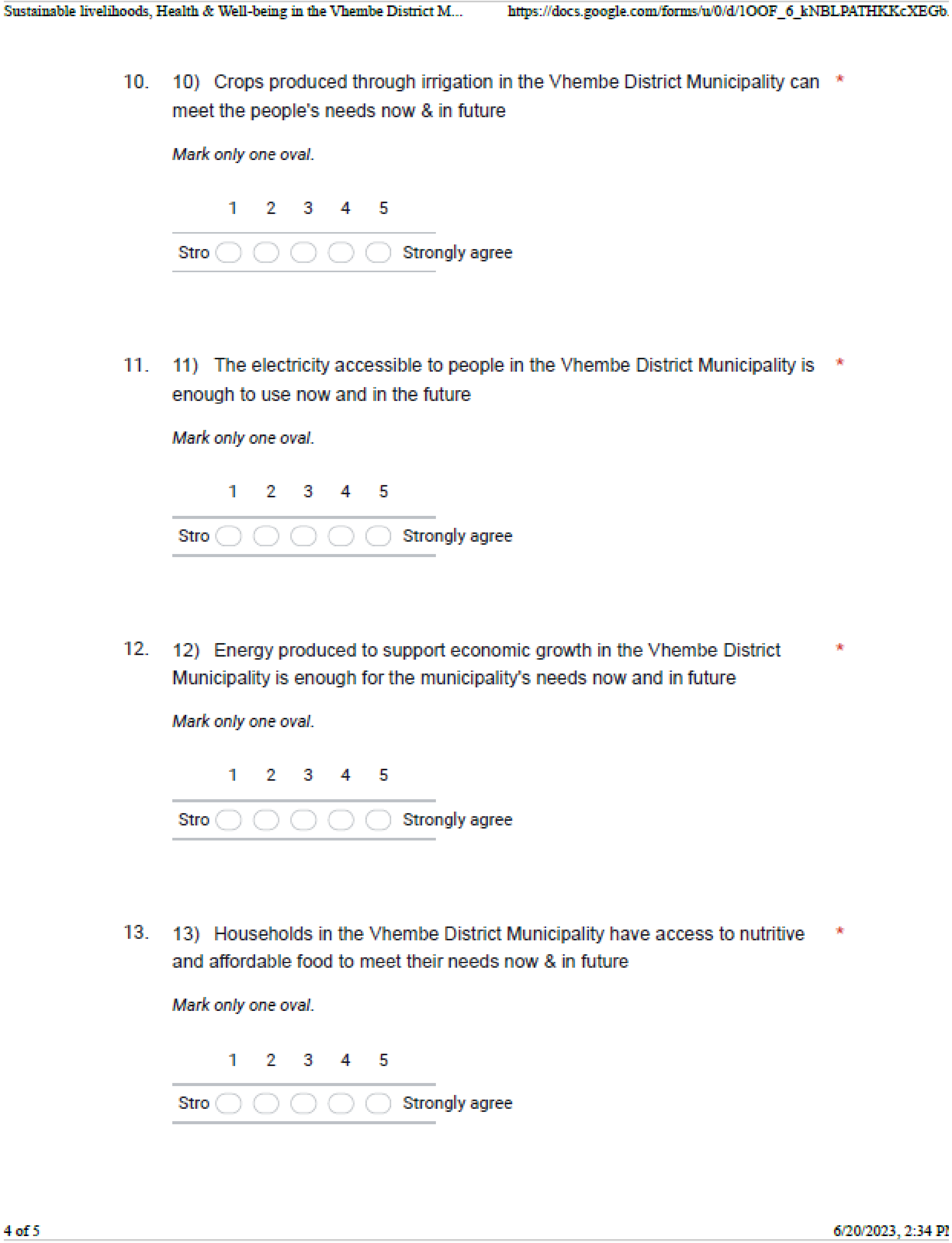

10. 10) Crops produced through irrigation in the Vhembe District Municipality can meet the people's needs now & in future *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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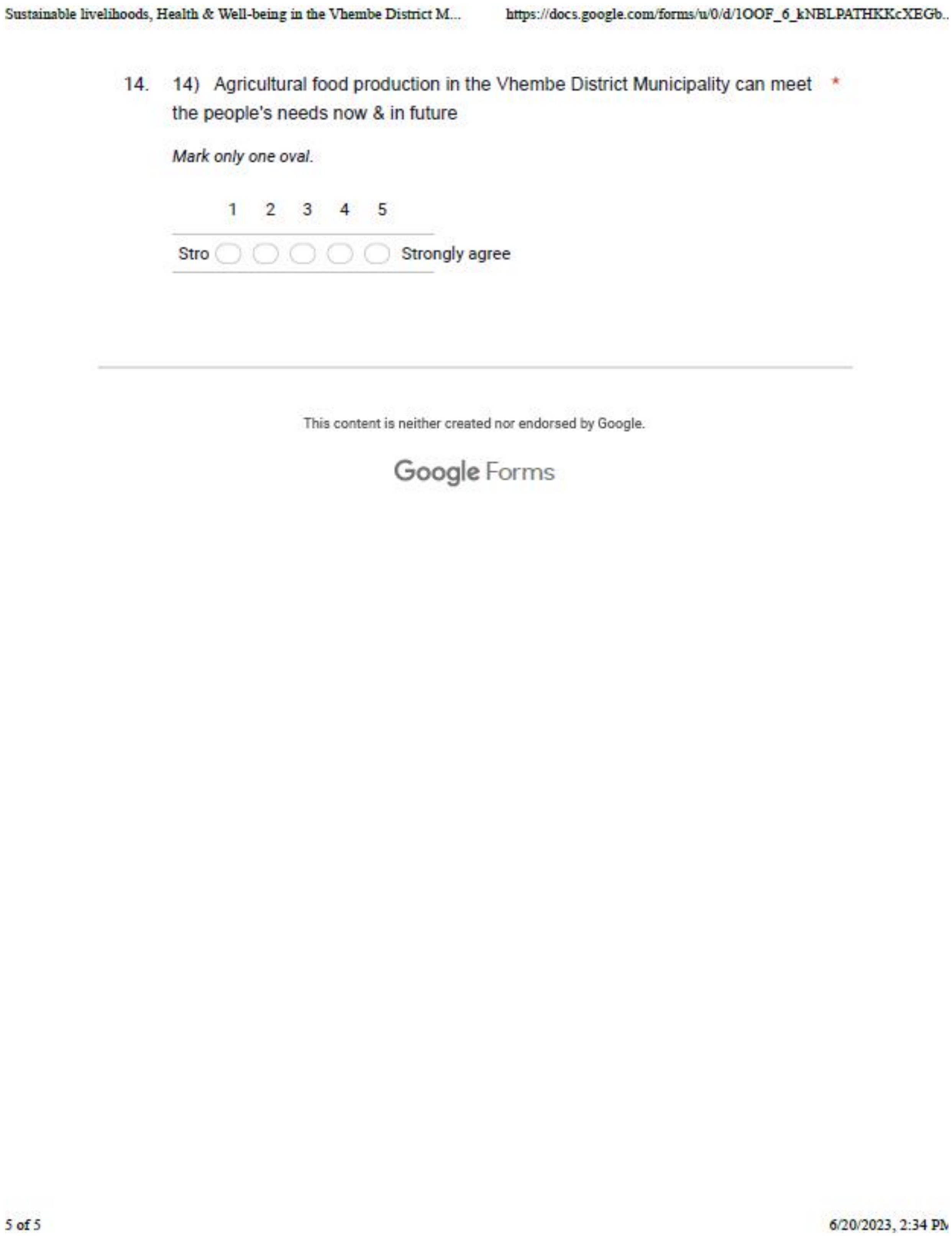

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14. 14) Agricultural food production in the Vhembe District Municipality can meet the people's needs now & in future *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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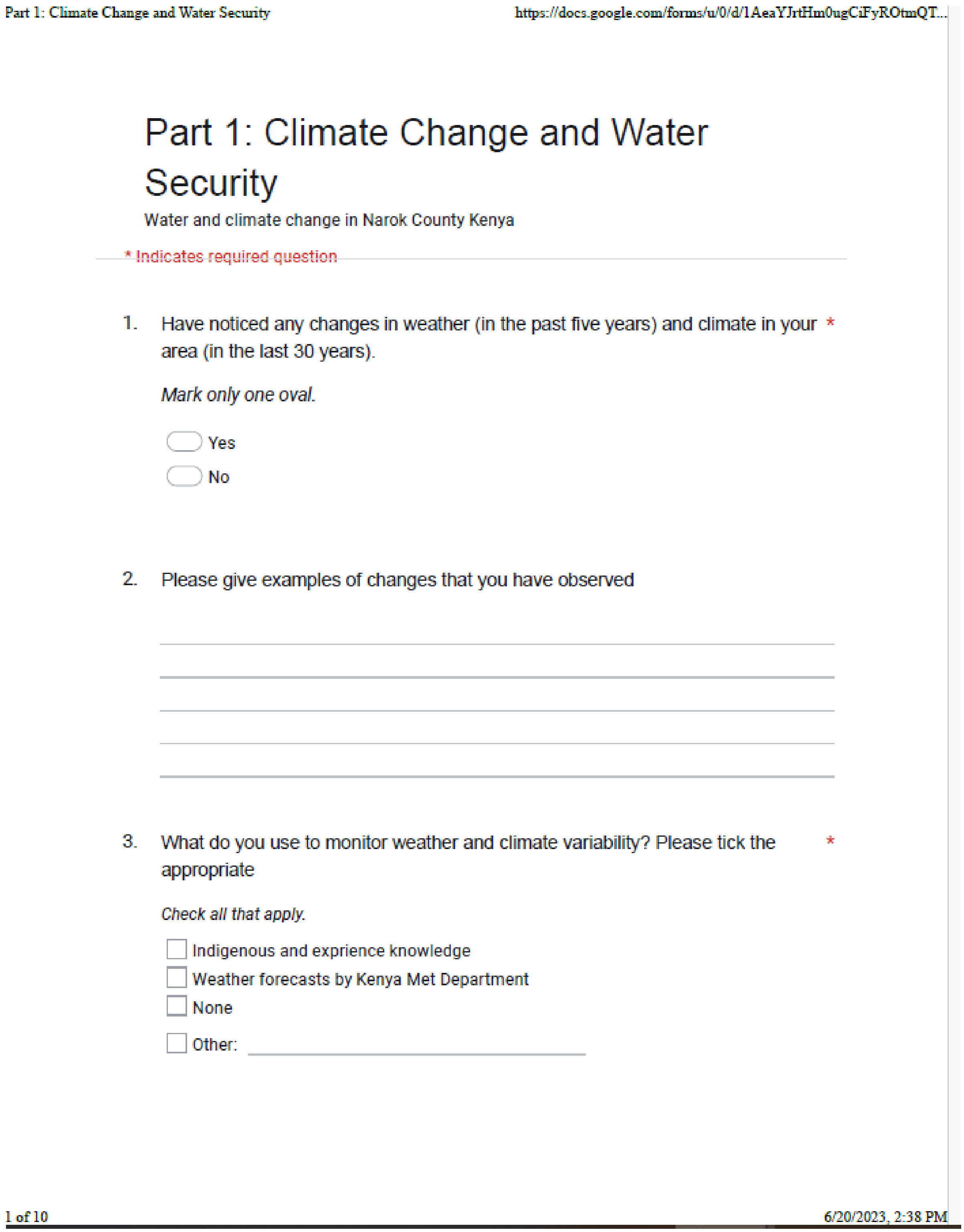
APPENDIX B



Part 1: Climate Change and Water Security https://docs.google.com/forms/u/0/d/1AeaYJrtHm0ugCiFyROtmQT...

Part 1: Climate Change and Water Security

Water and climate change in Narok County Kenya

* Indicates required question

1. Have noticed any changes in weather (in the past five years) and climate in your area (in the last 30 years). *

Mark only one oval.

○ Yes
○ No

2. Please give examples of changes that you have observed

3. What do you use to monitor weather and climate variability? Please tick the appropriate *

Check all that apply.

☐ Indigenous and exprience knowledge
☐ Weather forecasts by Kenya Met Department
☐ None
☐ Other: ____________

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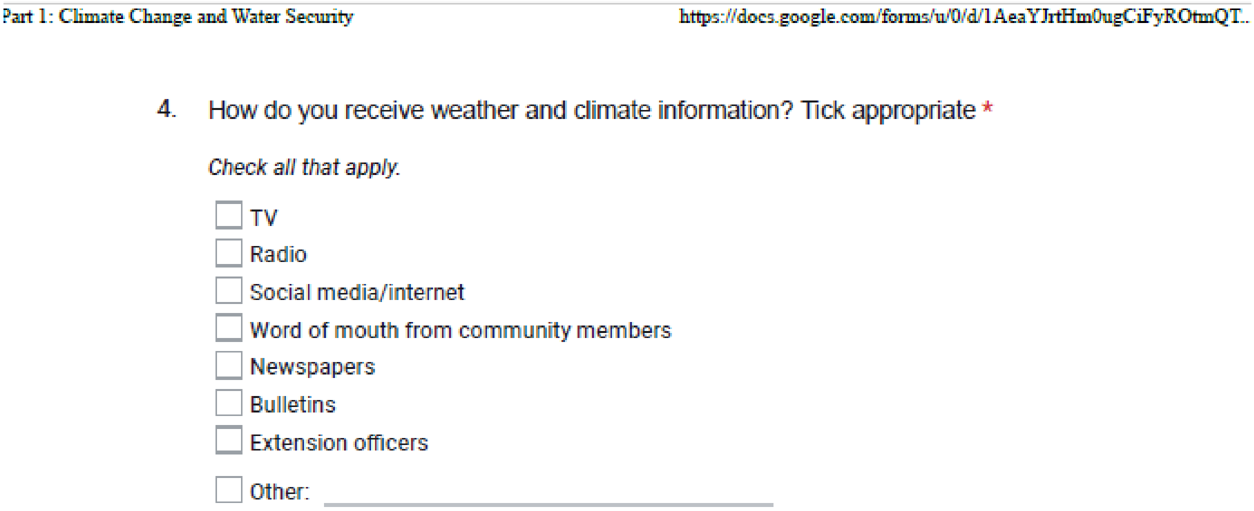

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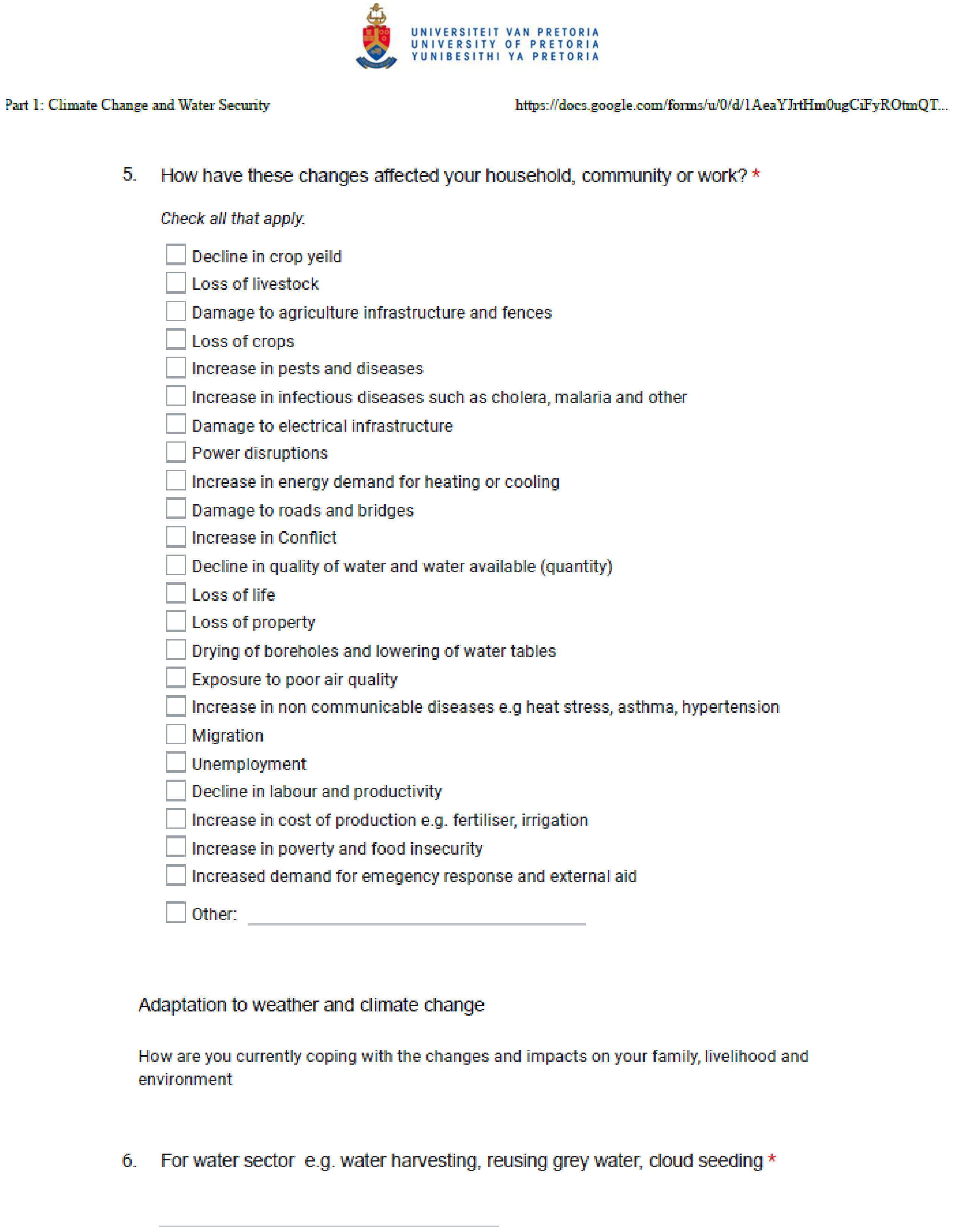
4. How do you receive weather and climate information? Tick appropriate *

Check all that apply.

☐ TV
☐ Radio
☐ Social media/internet
☐ Word of mouth from community members
☐ Newspapers
☐ Bulletins
☐ Extension officers
☐ Other: ____________________



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Part 1: Climate Change and Water Security https://docs.google.com/forms/u/0/d/1AeaYJrtHm0ugCiFyROtmQT...

5. How have these changes affected your household, community or work? *

Check all that apply.

☐ Decline in crop yeild
☐ Loss of livestock
☐ Damage to agriculture infrastructure and fences
☐ Loss of crops
☐ Increase in pests and diseases
☐ Increase in infectious diseases such as cholera, malaria and other
☐ Damage to electrical infrastructure
☐ Power disruptions
☐ Increase in energy demand for heating or cooling
☐ Damage to roads and bridges
☐ Increase in Conflict
☐ Decline in quality of water and water available (quantity)
☐ Loss of life
☐ Loss of property
☐ Drying of boreholes and lowering of water tables
☐ Exposure to poor air quality
☐ Increase in non communicable diseases e.g heat stress, asthma, hypertension
☐ Migration
☐ Unemployment
☐ Decline in labour and productivity
☐ Increase in cost of production e.g. fertiliser, irrigation
☐ Increase in poverty and food insecurity
☐ Increased demand for emegency response and external aid

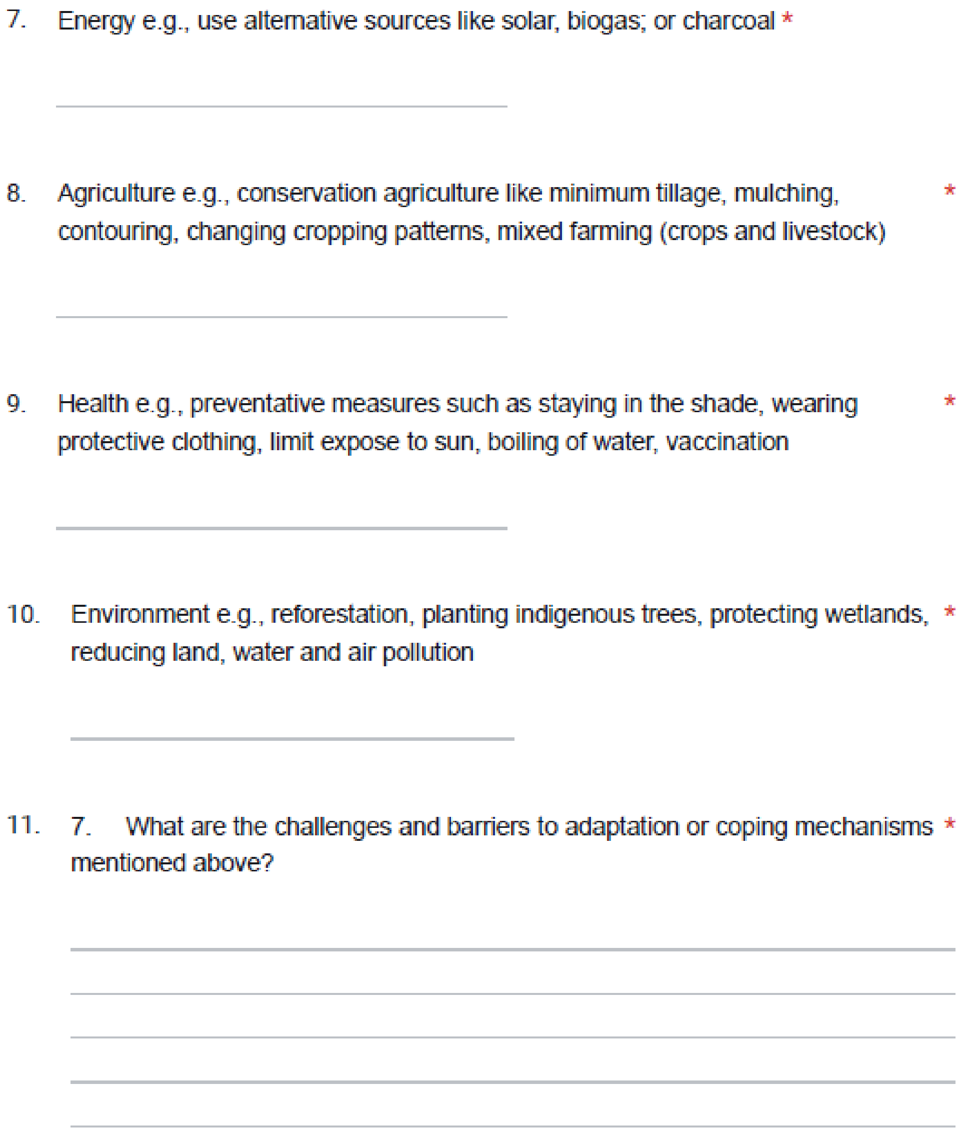
☐ Other: ____________________

Adaptation to weather and climate change

How are you currently coping with the changes and impacts on your family, livelihood and environment

6. For water sector e.g. water harvesting, reusing grey water, cloud seeding *

____



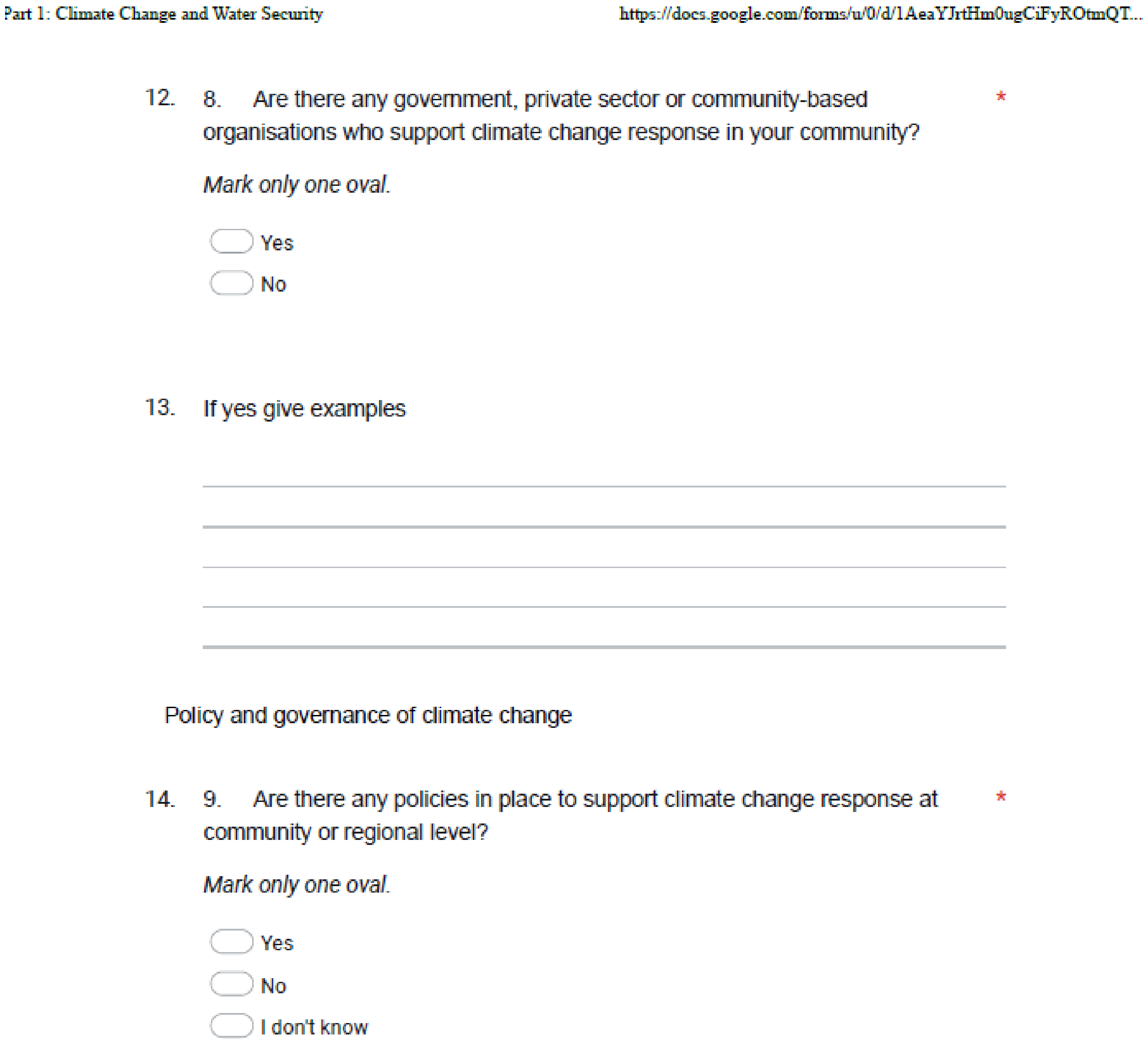
7. Energy e.g., use alternative sources like solar, biogas; or charcoal *

8. Agriculture e.g., conservation agriculture like minimum tillage, mulching, contouring, changing cropping patterns, mixed farming (crops and livestock) *

9. Health e.g., preventative measures such as staying in the shade, wearing protective clothing, limit expose to sun, boiling of water, vaccination *

10. Environment e.g., reforestation, planting indigenous trees, protecting wetlands, reducing land, water and air pollution *

11. 7. What are the challenges and barriers to adaptation or coping mechanisms mentioned above? *



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12. 8. Are there any government, private sector or community-based organisations who support climate change response in your community? *

Mark only one oval.

○ Yes
○ No

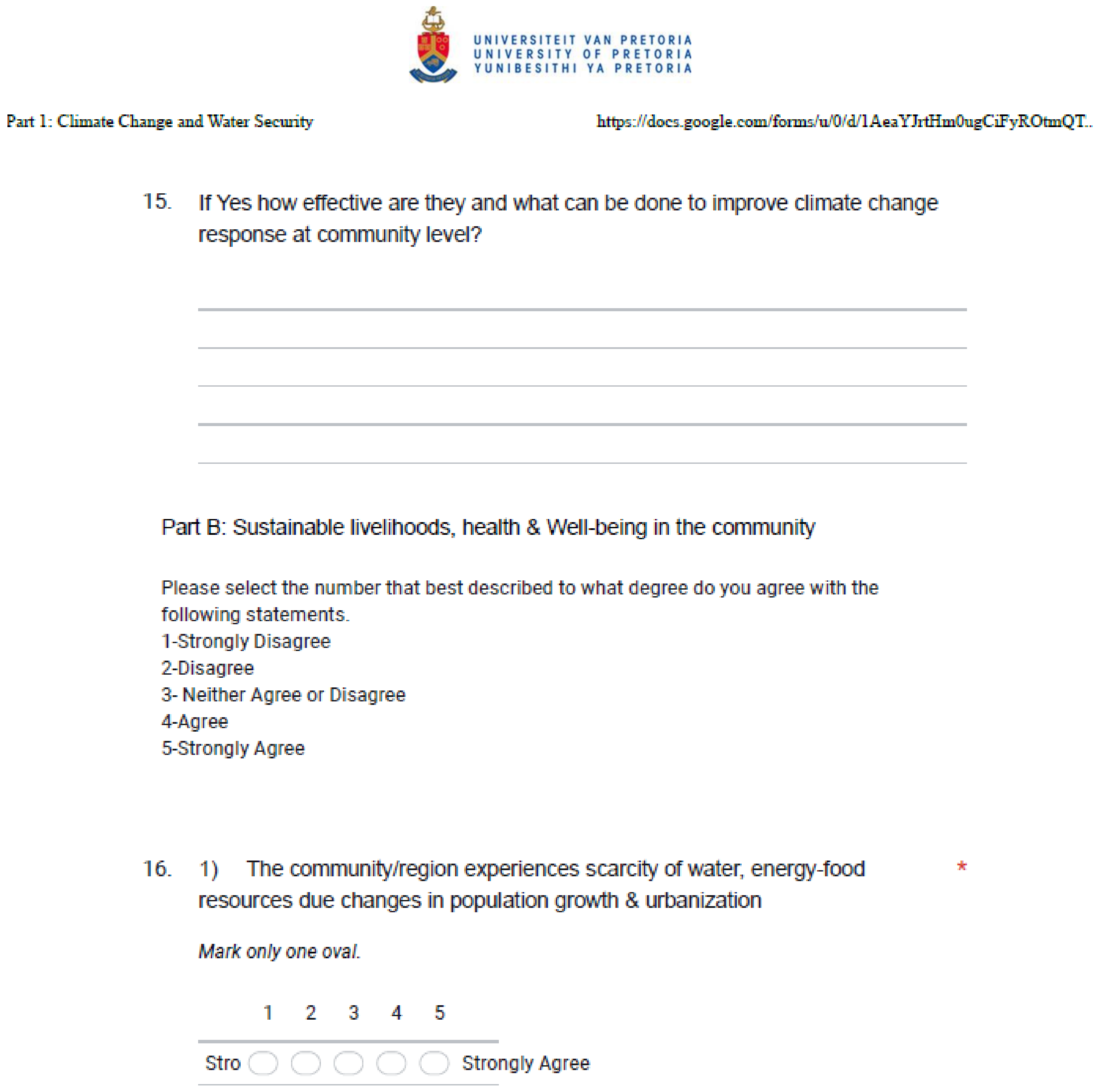
13. If yes give examples

Policy and governance of climate change

14. 9. Are there any policies in place to support climate change response at community or regional level? *

Mark only one oval.

○ Yes
○ No
○ I don't know



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15. If Yes how effective are they and what can be done to improve climate change response at community level?

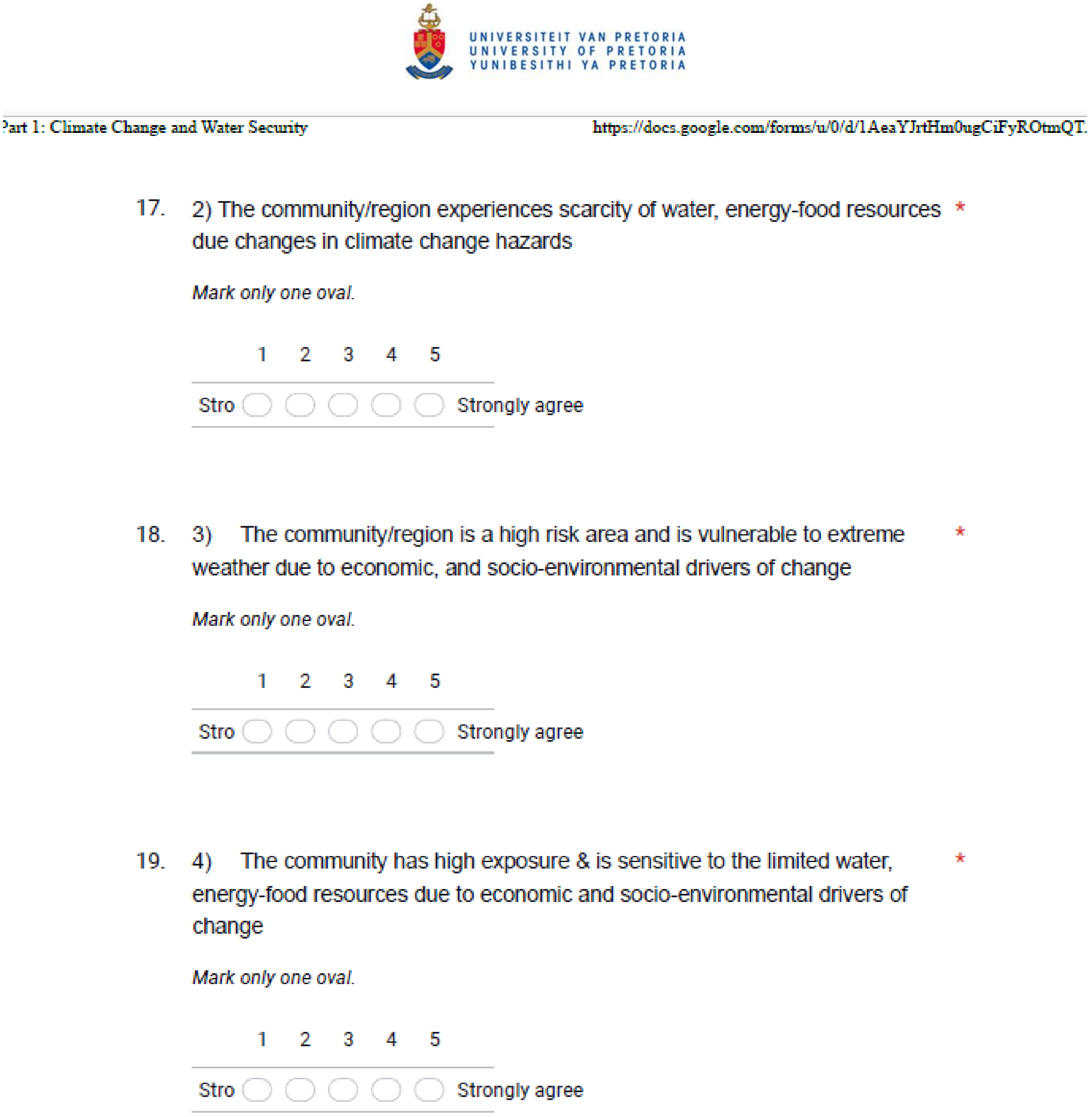
Part B: Sustainable livelihoods, health & Well-being in the community

Please select the number that best described to what degree do you agree with the following statements.
1-Strongly Disagree
2-Disagree
3- Neither Agree or Disagree
4-Agree
5-Strongly Agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly Agree



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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

18. 3) The community/region is a high risk area and is vulnerable to extreme weather due to economic, and socio-environmental drivers of change *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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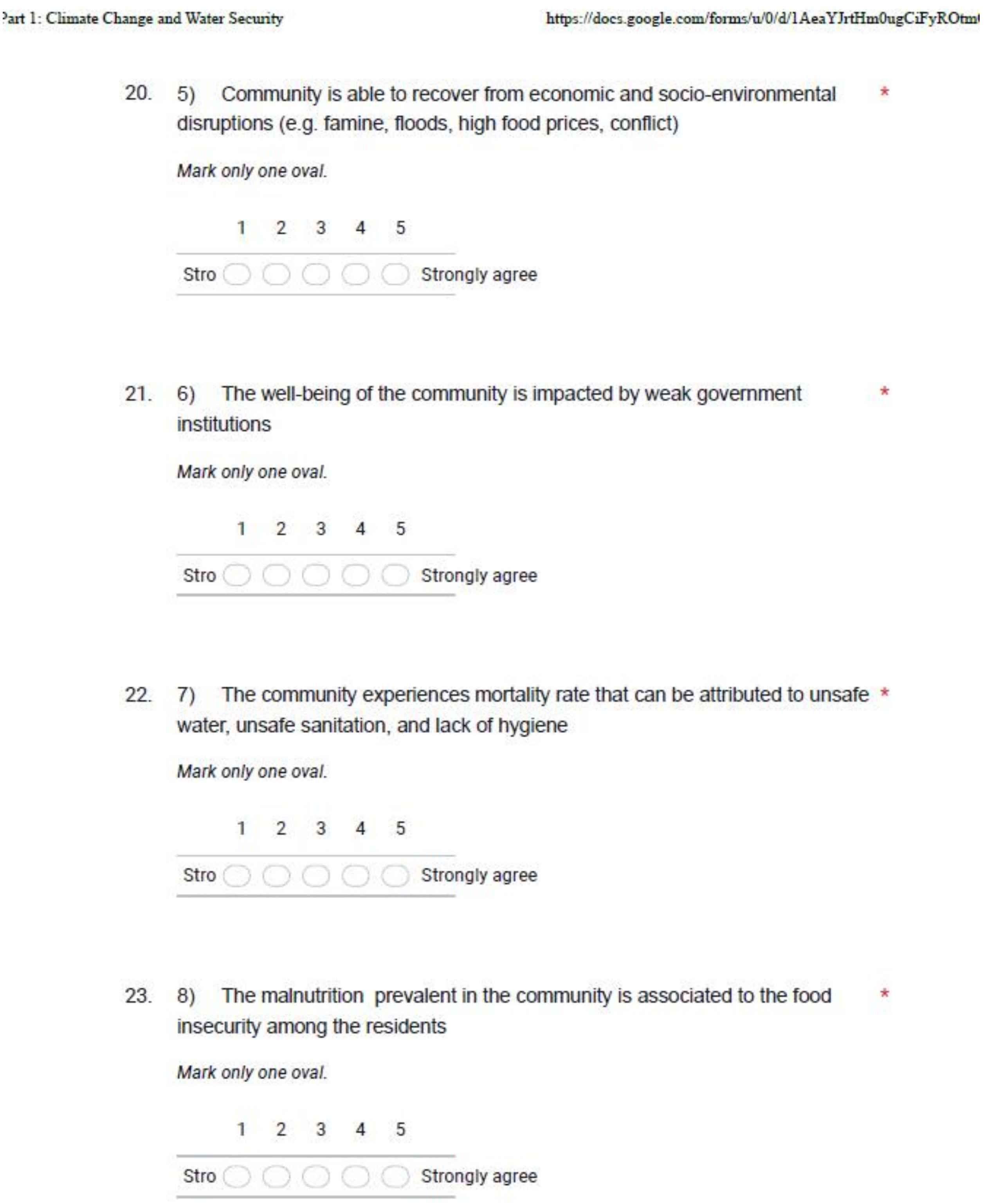

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20. 5) Community is able to recover from economic and socio-environmental disruptions (e.g. famine, floods, high food prices, conflict) *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

21. 6) The well-being of the community is impacted by weak government institutions *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

22. 7) The community experiences mortality rate that can be attributed to unsafe water, unsafe sanitation, and lack of hygiene *

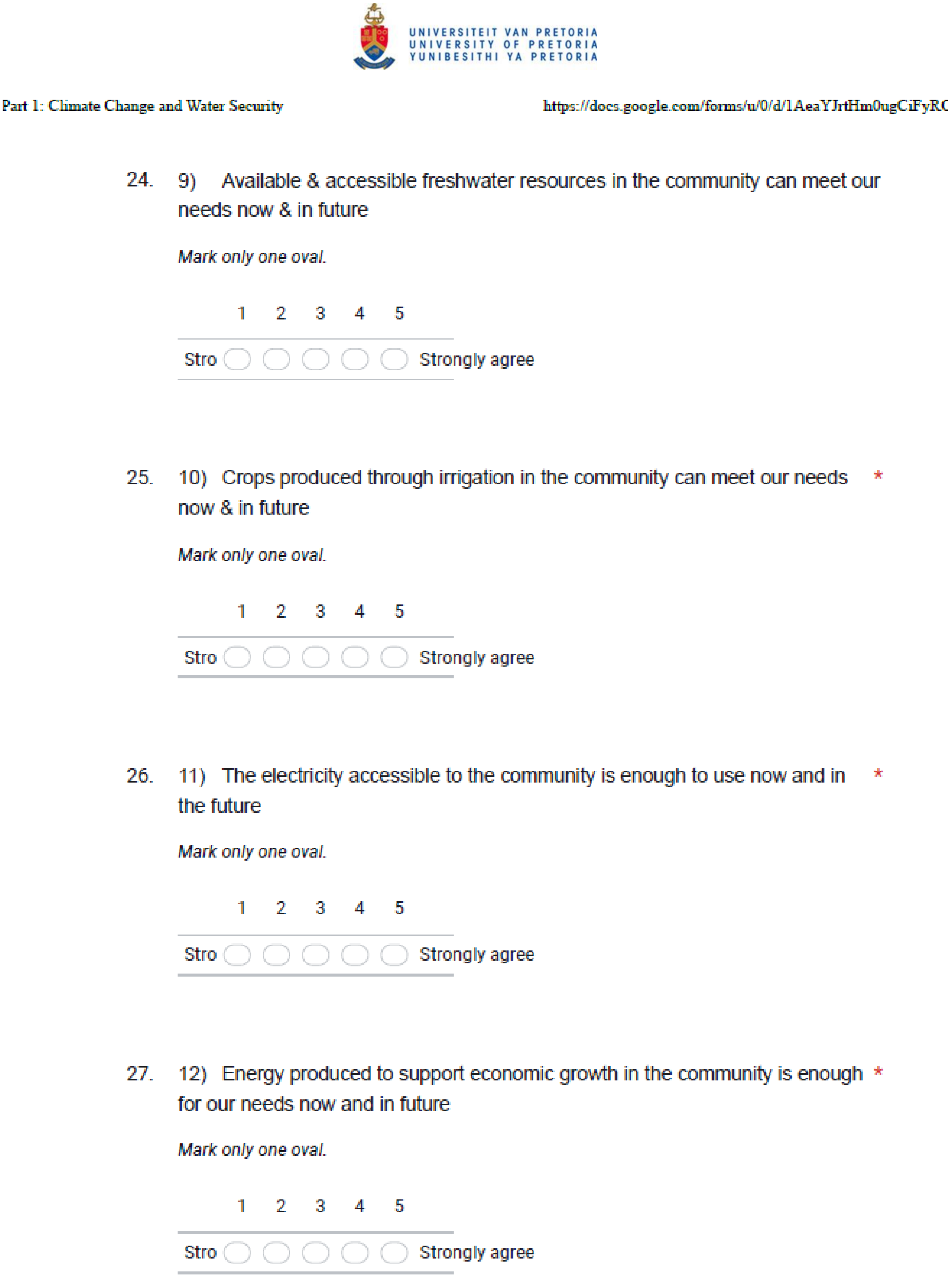
Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

23. 8) The malnutrition prevalent in the community is associated to the food insecurity among the residents *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree



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24. 9) Available & accessible freshwater resources in the community can meet our needs now & in future

Mark only one oval.

1 2 3 4 5

Stro ○ ○ ○ ○ ○ Strongly agree

25. 10) Crops produced through irrigation in the community can meet our needs now & in future *

Mark only one oval.

1 2 3 4 5

Stro ○ ○ ○ ○ ○ Strongly agree

26. 11) The electricity accessible to the community is enough to use now and in the future *

Mark only one oval.

1 2 3 4 5

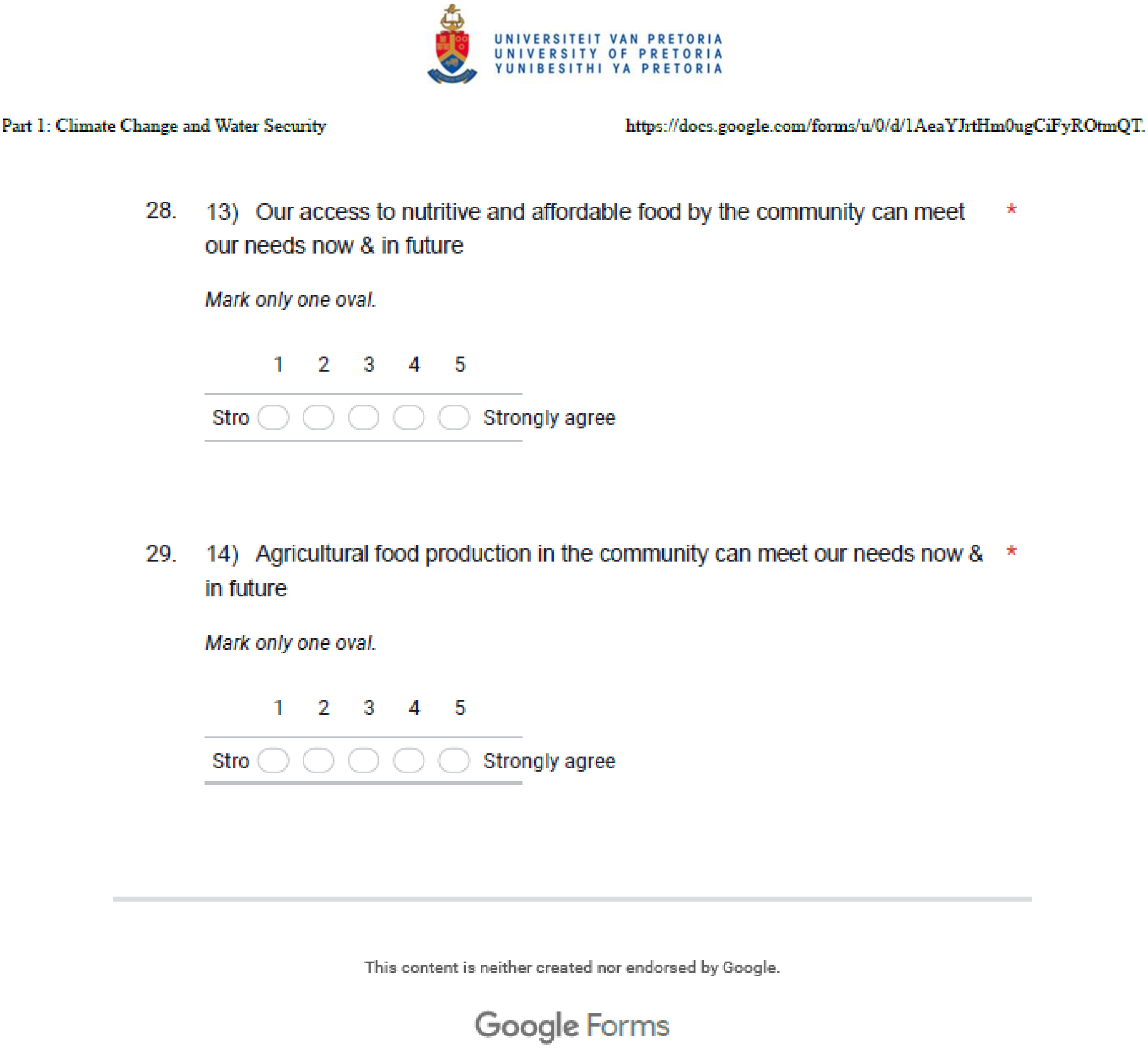
Stro ○ ○ ○ ○ ○ Strongly agree

27. 12) Energy produced to support economic growth in the community is enough for our needs now and in future *

Mark only one oval.

1 2 3 4 5

Stro ○ ○ ○ ○ ○ Strongly agree



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28. 13) Our access to nutritive and affordable food by the community can meet our needs now & in future *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

29. 14) Agricultural food production in the community can meet our needs now & in future *

Mark only one oval.

	1	2	3	4	5	
Stro	○	○	○	○	○	Strongly agree

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