THE WATER-ENERGY-FOOD NEXUS AS A CATALYST FOR ENHANCING COOPERATIVE GOVERNANCE FOR CLIMATE CHANGE ADAPTATION IN SOUTH AFRICA

Report to the
Water Research Commission

prepared by

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Executive summary

The discourse on food, water, and energy security is driven by the growing pressure on natural resources. The demand for food, water, and energy is growing steadily, but the resources required to generate them are limited and, in many cases, they are decreasing. Water, energy and land issues are intrinsically connected. Multiple objectives are at stake and must be addressed concurrently. The nexus approach aims to identify tradeoffs and synergies of water, energy, and food systems, internalize social and environmental impacts, and guide the development of cross-sectoral policies. Overlaid to the challenges of managing the intersections of the water, energy and food nexus is the phenomenon of climate change. Climate change provides an added stress on approaches to manage the WEF nexus.

However, the focus on adaptation has remained sectoral; most adaptation approaches regard adaptation largely as a local issue with a community or ecosystem focus; and it is not yet clearly understood how the adaptation concept can be applied to ensure food, water, and energy security nexus.

The aims of this project were to:

(i) Analyse the measures on climate change adaptation, seen through the WEF nexus in the Province of Mpumalanga. Lessons learned will be applied across the country when the project goes into the next phase under the WRC.

(ii) Highlight the significance of provincial government in the interplay between governance initiatives on the WEF nexus and climate change adaptation.

(iii) Describe and analyse the influence and the confluence of current climate change adaptation planning at a provincial level with the WEF nexus.

(iv) Facilitate an informed and coherent implementation of WEF nexus measures to enhance the effectiveness of implementing climate change adaptation measures.

We started by undertaking a comprehensive literature review of the WEF nexus studies in Africa using bibliometric analysis and concluded that there is a need for more studies on the WEF nexus in Africa, that these studies should focus more on the application or practice of WEF nexus considering the impacts of climate change, and that detailed studies to balance under-represented concepts as shown in the thematic progression analysis of concepts of the WEF nexus in this study. We then described the study area (Mpumalanga Province) which was followed by the methodology. The methodology used in this study was anchored on the use of geospatial techniques.

We then looked at the complementarities / co-benefits / synergies of the WEF nexus-based adaptation. We did this by locating ongoing- and recently completed adaptation projects that contribute to the WEF nexus in Mpumalanga province in different land use and land cover classes. We then determined the district municipalities in Mpumalanga Province that had a higher hotspot for climate change adaptation projects that contribute to the WEF nexus. We found high concentrations of adaptation-related interventions in the Ehlanzeni district municipality, followed by the Nkangala district municipality. While Gert Sibande district municipality showed few interventions that had been implemented.

We then looked at the trade-offs of the WEF nexus-based adaptation in Mpumalanga. We did this by (i) assessing the accuracy of land use and land cover change in Mpumalanga, (ii) analyzing land use and cover and its impacts on WEF nexus resources over a 30-year period

(1990-2020) in Mpumalanga and by, (iii) determining the impact of land use and land cover on the WEF nexus.

Our results showed that the major land use and land use changes in Mpumalanga are related to mining, agriculture, grasslands, woodlands, and built-up areas. All of these have a direct impact on water supplies, energy sources, and food production. Our results suggest that:

(a) There is a need for comprehensive tools that allow decision-makers to understand trade-offs and synergies within the WEF nexus and contribute to wise resource allocation and use.
(b) Understanding LULC changes and estimating their effects on WEF nexus resources can give government decision-makers a scientific foundation to improve the current land development and planning policies.
(c) There is the need to improve cross-sector cooperation and coherence of efforts to properly tackle the WEF nexus-based challenges.

Regarding new knowledge generated in this project: the project developed a geospatial visualization tool that included land use and land cover, extreme climatic variables, and topographic and soil variables. This tool was used to visualize the products (for example, the modelling results) presented in this study. Taken together, this geospatial tool efficiently linked planning and implementation of scalable projects in Mpumalanga province.

Also, the project produced wall-to-wall mapping of land use for the Mpumalanga province. These wall-to-wall provincial maps should enable departments responsible for the governance of the components of the WEF nexus to render services related to the WEF nexus to and for the communities in their jurisdictions more efficiently.

The outputs of this project can also be used to identify and quantify arable land in Mpumalanga and provide projections of the size of populations that can be supported by natural resources (WEF) sustainably.

Regarding capacity building, a MSc student, and a Postdoc, both from the University of Pretoria, contributed to this project. Regarding knowledge dissemination and technology transfer, a review paper on the bibliometric analysis of the WEF nexus in Africa (Chapter 2 of this report) has been published in the Sustainability Journal. In addition, a conference paper has been submitted to the African Association for Remote Sensing of Environment (AARSE). Furthermore, a policy review paper and a paper focusing on "the spatial linkages of climate change adaptation projects or intervention with extreme climatic variables, other environmental and socio-economic variables" are being drafted. Finally, a MSc thesis will be submitted to the University of Pretoria in 2023.

Acknowledgements

The project team is very grateful to the Water Research Commission (WRC) for the financial, administrative, and technical support and guidance throughout this project. We want to acknowledge the support received from Prof. Sylvester Mpandeli and Ms. Sandra Fritz. The funding from WRC ensured a productive collaboration between the CSIR and the University of Pretoria, while also allowing the project team to contribute to the WEF community of practice in South Africa. Importantly, the funding from the WRC covered the costs of the MSc student at the University of Pretoria.

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Reference group committee members were:

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LIST OF ABBREVIATIONS AND ACRONYMS

AEA…………………	Albers Equal Area
AUC………………...	Area Under Curve
CABLE……………..	CSIRO Atmospheric Biosphere Land Exchange
CCAM………………	Conformal-Cubic Atmospheric Model
Cdd………………….	Consecutive Dry Days
CMIP5…………….....	Coupled Model Intercomparison Project Phase 5
CSIR………………....	Council for Scientific and Industrial Research
CSIRO………………	Commonwealth Scientific and Industrial Organization
CWD………………...	Consecutive Wet Days
DEM…………………	Digital Elevation Model
DFFE…………….....	Department of Forestry Fisheries and the Environment
FEW…………………	Food-Energy-Water
GCM………………...	Global Climate Model
GDP…………………	Gross Domestic Product
GeoTIFF…………...	Geographic Tagged Image File Format
GLM………………...	Generalized Linear Model
LULC…………….....	Land use and Land cover
MCP……………......	Multiple Country Publications
NCCRD………….....	National Climate Change Response Database
NIC………………….	National Intelligence Council
NLC…………………	National Land Cover
PCC………………....	Post-Classification Comparison
ROC…………………	Receiver operating Characteristic
SADC……………......	Southern African Development Community
SAEON……………..	South African Environmental Observation Network
SCP…………….......	Single Country Publications
SDGs………………..	Sustainable Development Goals
SFW…………………	Soil-Food-Water
SSTs…………………	Seas-Surface Temperatures
UK………………......	United Kingdom
UNFCCC……………	United Nations Framework Convention on Climate Change
USA………………….	United States of America
USGS………………..	United States Geological Survey
UTM…………………	Universal Transverse Mercator
VIF…………………...	Variance Inflation Factor
VOSviewer……........	Visualization of similarities
WE…………………...	Water-Energy
WECC…………….......	Water-Energy-Climate Change
WEF…………………	Water-Energy-Food
WEFBH……………....	Water-Energy-Food-Biodiversity Health
WF…………………...	Water-Food
WLF…………………	Water-Land-Food
WOS………………....	Web of Science
WRC………………....	Water Research Commission

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

1.1.1 Climate change and the WEF nexus

A "nexus" is the convergence of several issues. Nexus approaches or Nexus research represents contemporary ways of examining the links and feedback within and between socio-economic sectors geared towards the creation of job opportunities and management of greenhouse gas emissions. A useful framework for resolving complex challenges is provided by the Water-Energy-Food nexus concept. For instance, human well-being, poverty reduction, and sustainable development are dependent upon water, energy, and food. All three are interconnected because the production of food requires water, the management of water (extraction, treatment, and redistribution) requires energy, and hydro-energy production (a major source of energy in Southern Africa) requires water (Flammini *et al.* ,2017; Bazilian *et al.* 2011; Mabhaudhi *et al.* 2016; Rasul, 2016). A change in one area impacts the other two. Interconnections like these are described as the Water-Energy-Food (WEF) nexus (Mabhaudhi *et al.* 2016; Leck *et al.* 2015), which leads to economic development and social security when implemented well (Mabhaudhi *et al.* 2016). Nexus approaches are systems-based approaches which consider the interconnectedness and interdependencies between sectors when examining projects, strategies, policy options, and investment strategies in complex socio-environmental systems. The initiative integrates research, management, and governance across sectors and scales. It assumes that there are biophysical and environmental limits to the degree to which resources can be tapped or pollutants can be absorbed, and exceeding these limits could have catastrophic impacts, whether immediately or in the future.

Global demand for water and food is expected to increase by over 50% by 2050, while global energy demand will nearly double, leading to competing demands on limited resources (IRENA, 2015). Consequently, the challenges will aggravate other factors such as malnutrition, inadequate health care, and migration (Adeyeye *et al.* 2017; Bain *et al.* 2013). Climate change has an impact on natural and human systems worldwide (IPCC, 2014). Water scarcity and reduced crop yields are some of the negative consequences of increasing temperatures and changing precipitation patterns, which affect all dimensions of the WEF nexus. Extreme weather events linked to climate change, such as heat waves, droughts, and floods, alter ecosystems and the services they provide. There are some regions of the world that are particularly vulnerable to climate variability, and they require adaptation measures to ensure sustainable future water, energy, and food security.

Considering mounting evidence of climate change impacts, as well as growing population demand (Nhamo *et al.* 2018), a cross-sectoral approach such as the WEF Nexus is necessary to promote sustainable development. With climate change, the complex interrelationships in the WEF nexus become more uncertain and resources must be used sustainably. There is a need for comprehensive tools that allow decision makers to understand trade-offs and synergies within the WEF nexus and contribute to wise resource allocation and use. In context of emerging constraints on sustainable development, the WEF nexus develops a framework for managing synergies and trade-offs among water, energy, and food. As a socio-ecological systems approach, the WEF nexus offers a sustainable solution to complex problems such as climate change adaptation (Mabhaudhi *et al.* 2016), while still promoting economic development in regions across the globe. Climate change impacts and responses are generally cross-sectoral, which necessitates a coordinated approach within the three highly exposed sectors. This is known as the water-energy-food nexus.

Climate change is most likely to have adverse impacts on South Africa's water resources, arable land, biodiversity, as well as primary industries, amplifying tensions, and trade-offs. South Africa has uneven rainfall distribution, making the country prone to the impacts of adverse climate change. The country has a predicted rise in temperature of 3°C by the end of the century if greenhouse gas emissions are severely cut or by as many as 6°C if they are not. In South Africa, the impact of climate change on freshwater resources could exacerbate existing and create new challenges, such as extreme weather events and changing rainy seasons. In the future, this could affect a wide range of economic sectors and livelihoods, as well as the development of infrastructure due to water quality issues. The country's efforts to transition to a green and circular economy, and the emphasis it places on resource-efficient, low-carbon, and socially inclusive technologies and development strategies offer ample opportunities for implementing the WEF nexus across the various spheres of government. Despite all the research and development interventions, clear and decisive national leadership is critically important in the realization of the WEF-nexus goals.

1.1.2 Climate change adaptation – interphases between water, energy and food strategies

Adapting to climate change is a global societal challenge to which governments at all scales, the private sector, academia and civil society groups can contribute. The study by Agarwal *et al.* (2012) investigated the role and the relationships between national and local institutions for adaptation and brought attention to the need for better mechanisms and processes for sharing information both vertically and horizontally to facilitate adaptation. A major part of the global response to climate change, led by the United Nations Framework Convention on Climate Change (UNFCCC), has prioritized adaptation as a vital response. In recent years, climate change adaptation has become the discussion point of climate and global change literature, with issues of water, energy, and food at the forefront (Madzwamuse, 2010; Fiske *et al.* 2014). As a multilevel and multi-actor endeavour, climate change adaptation requires high levels of collaboration, facilitated through effective partnerships in order to achieve positive adaptation outcomes and avoid maladaptation (Adger *et al.* 2005; Barnett and O'Neill, 2010). A primary objective of climate change adaptation is to reduce vulnerability both to climatic and non-climatic changes. As a result, adaptation has close ties to ensuring sustainable use and management of water, energy, and food, which are required for sustainable development. Adaptation achieves this by addressing water, energy, and food security challenges harmoniously.

This project was propelled by the following challenges:

- An urgent need to enhance intergovernmental planning and coordination by the government departments.
- The focus on adaptation has remained sectoral.
- Most adaptation approaches regard adaptation largely as a local issue with a community or ecosystem focus.
- It is not yet clearly understood how the adaptation concept can be applied to ensure food, water, and energy security nexus.

- Lack of effective application (and resources) of Research and Development tools (including Geospatial tools), including the Monitoring and Evaluation of interventions in the WEF nexus space.

1.2 RATIONALE

1.2.1 Problem statements

To build resilience to the negative impacts of climate change in the WEF nexus, planners and decision-makers need to consider integrated responses that do not foreclose future options, but develop the ability to respond to unforeseen events, monitor indicators so that changes can be observed, and adopt flexible planning to allow appropriate responses as conditions change. The process should be informed by available national resources and constant communication with the research and civil society communities.

Problem 1: An urgent need to enhance intergovernmental planning and coordination by the government departments

Inadequate planning and lack of clear strategy implementation in the government sectors that pays little attention to important nexus elements could lead to inappropriate resource allocation, and high level of unsustainable outcomes, both environmentally and socio-economically. Decisions made now, need to take into consideration future resource constraints. Failure to do so could lead to costly mistakes. Functionally, integrated planning, using a nexus-type approach, can have major benefits to sustainable development, and this will reflect through optimization of resource use, leading to increased creation of sustainable jobs, economic growth and reductions in inequality. Not implementing type nexus-type approaches can lead to inappropriate resource allocation and socio-environmental collapses, leading to job losses and environmental damage.

Problem statement 2: The focus on adaptation has remained sectoral.

Insufficient attention has been given to cross-sectoral issues. Particularly the harmonization of sectoral goals and systemization of decision-making, which considers cross-sectoral dimensions has not been a concerted focus of governance in South Africa. As such, most government-led adaptation responses have a sectoral approach and are designed to meet sectoral goals. That is, there is limited consideration or coordination of cross-sectoral interactions. This happens even among the obviously inter-related climate-sensitive sectors such as water, energy and food. As such, this sectoral approach has not enabled planners and decision-makers to respond to the key underlying question on climate change adaptation of whether the observed adjustments and changes to perceived climate risks represent evidence of a societal shift towards a well-adapting society or are merely unconnected actions of sectors motivated by different stimuli.

It is critical to strengthen the WEF nexus perspective in public sector planning and strengthen the capacity for diagnosing interlinkages among inter-dependent sectors and bringing these inter-dependencies to the sight of planning and decision-making processes. Therefore, to facilitate moving from a sectoral approach to a holistic approach, an appropriate framework is required. A result could be cost savings from the reduction of duplicated interventions, thus leading to the scaling up of significant measures.

Problem statement 3: Most adaptation approaches regard adaptation largely as a local issue with a community or ecosystem focus.

Recent years have seen a greater emphasis of the role and importance of local context in adaptation, arguing that geographic, socio-economic and institutional factors differ vastly across constituencies and that, consequently, adaptation efforts need to be embedded in local situations to be effective and fit-for-purpose (Preston, 2013; Measham *et al.* 2011; Aall, 2012). Unfortunately, this approach misses the opportunity of the significant role of the national, regional, and global policies and institutions that shape adaptation options and choices. Local adaptation approaches often prove unsustainable owing to inadequate institutional support (Agrawal, 2010).

Problem statement 4: It is not yet clearly understood how the adaptation concept can be applied to ensure food, water, and energy security nexus.

A recently completed report to the Water Research Commission indicated that much of the WEF nexus information that has been produced has a regional SADC focus (Mabhaudhi, *et al.* 2018). This is despite the widely held view that climate change adaptation is intrinsically linked to water, energy, and food security and the pursuit of understanding the impacts of climate change on water and agriculture. Failure to consider the nexus of water, energy, and food in resource assessments and policy making opens an opportunity for contradictory strategies and inefficient use of resources.

There is a growing understanding that the different interfaces in the water, energy and food nexus will be critical for climate change adaptation. However, there is no common understanding of how the WEF nexus can contribute to successful adaptation in South African circumstances. Indeed, there is broad recognition that successful adaptation will require interventions that address the full spectrum of challenges, including the underlying causes of vulnerability, managing climate risks, and building response capacity. Equally, it is well established that adaptation will not be effective unless it is integrated into development policy, and that development processes need to be aligned to create the necessary enabling conditions. Yet, there is a lack of understanding on how to implement the WEF nexus for specific circumstances that are prevalent in South Africa, to ensure successful adaptation.

It is well-known that having the knowledge, capacity and resources to undertake adaptation does not guarantee action (Hanemann, 2000; Repetto, 2008; Moser, 2013). Common barriers to adaptation that have been documented include: (i) the public good nature of threatened resources; (ii) a failure in collective decision-making; (iii) uncertainty over information interfering with adaptation decisions (iv) lack of clarity over who is responsible for the action (public or private sector) (Tompkins and Adger, 2005).

1.2.2 Theory of change

Focusing on the synergies and trade-offs of the WEF nexus is a potential strategy for climate change adaptation to address current and future challenges of resource management, poverty, hunger, and inequality, in a systematic way. We recognise that:

(i) Solutions for climate change adaptation take many shapes and forms, depending on the unique context of a community, business, organization, country or region. That is, there is no 'one-size-fits-all-solution' when it comes to adaptation responses.

(ii) Successful adaptation does not only depend on government. It also depends on the active and sustained engagement of a wide variety of stakeholders, as well as effective management of knowledge.

(iii) Adaptation to the impacts of climate change may be undertaken across various levels of governance (local, provincial, national, regional).

(iv) There are four general components of adaptation: (a) assess impacts, vulnerability and risks (b) planning for adaptation (c) Implementation of adaptation measures and (d) Monitoring and Evaluation of adaption measures.

The overarching objective of this project is to identify a workable governance framework that supports WEF nexus-adaptation initiatives. We aim to do this by focusing on the provincial level of planning for climate change adaptation for this specific project. For this project, the Mpumalanga Province was selected to undertake the baseline assessment.

The inadequate understanding of the social, economic, and environmental conditions prevailing in Mpumalanga Province, the complexity of the associated decision-making processes, and the relevance of temporal and spatial scale in enabling adaptation, highlights a knowledge gap in the information needs and policy support required by stakeholders in the WEF sectors. This shortfall has prompted the development of this project, and closer collaboration with the Department of Agriculture, Rural Development and Environmental Affairs in Mpumalanga Province

1.2.3 Evolution of WEF nexus research in South Africa

Water, energy and food (WEF) form the basis of a resilient economy and society. This reality is even more pronounced in South Africa, where poverty and inequality overlay a water-scarce country with little arable land and dependence on oil imports. South Africa is faced with the difficulties of developing the economy in an equitable, resilient and inclusive manner without irreversibly degrading renewable resources or failing to realise the full development potential of non-renewable resources. Tensions between the increasing demand for and use of natural resources (e.g. water, land and energy) to support development on the one side, and availability and quality of such resources on the other are exacerbated by a decreasing trend in the quality of the state of the natural environment. Facing a growing and more affluent world population, changing climate and finite natural resources, resource use management (e.g. world food systems, water management, access to energy) will have to change in the future. Recognising that the relationship between economic growth and environmental sustainability is complex, it is widely accepted that informed and least regretful approaches to the use of natural resources, explicitly informed by a clear understanding of trade-offs, are required if the consequences of overexploitation and climate change are to be avoided.

The South African natural environment and its resources provide a unique set of well-documented opportunities and challenges to future socio-economic development (LTAS, 2013; Carter and Gulati, 2014; Chikulo, 2014; Ziervogel, *et al.* 2014). The government is committed to eliminating poverty and reducing inequality by 2030, as set out in key national policy documents (NPC 2011; NCCRP, 2011) and in the international agenda for Sustainable Development Goals (SDGs) to which the government has subscribed. The achievement of these commitments contained in these policy documents requires faster and more equitable economic growth, and higher investment and employment, with a clear understanding of trade-offs and synergies central to sustainable development. Since informed use of natural capital is essential to economic development, plans to achieve these objectives require the least regretful decision-making, and informed consumption and utilization of South Africa's resources (NPC, 2011).

1.3 AIMS AND OBJECTIVES

1.3.1 General aims

- To analyse the measures on climate change adaptation, seen through the WEF nexus in the Province of Mpumalanga. Lessons learned will be applied across the country when the project goes into the next phase under the WRC.
- To highlight the significance of provincial government in the interplay between governance initiatives on the WEF nexus and climate change adaptation.
- To describe and analyse the influence and the confluence of current climate change adaptation planning at a provincial level with the WEF nexus.
- To facilitate an informed and coherent implementation of WEF nexus measures to enhance the effectiveness of implementing climate change adaptation measures.

CHAPTER 2: COMPREHENSIVE LITERATURE REVIEW USING BIBLIOMETRIC ANALYSIS

2.1. INTRODUCTION

The water, energy, and food (WEF) nexus is deeply complex (Botai *et al.* 2021) and interconnected, as actions in one sector will inevitably affect actions in the other two sectors, hence there are trade-offs in the decision-making process. Because the production of food requires water, the management of water (extraction, treatment, and redistribution) requires energy, and energy production, whether, from coal, nuclear or hydroelectric power plants, hydro-energy production (one of the major sources of energy in Southern Africa besides burning coal) requires adequate water supply (Bazilian *et al.* 2011; Mabhaudhi *et al.* 2016; Rasul, 2016; Leck *et al.* 2015). Making the components of WEF accessible and affordable is vital for life and livelihoods. As such, access to all three sectors of the WEF nexus is crucial for progress toward achieving sustainable development goals (SDGs).

Africa's diverse ecosystems produce a wide range of goods and services that are crucial to supplying food, water, energy, and medicine, and sustaining livelihoods on the continent (IRENA, 2015). However, due to the combination of multiple stresses, such as the impacts of colonization, dependence on climate-sensitive rainfed agriculture, poor infrastructural development, lack of functional institutional arrangements, low adaptive capacity and decades'-long failure by African leaders to adequately invest in their respective country's electricity and water sectors there is increasing uncertainty to the security of WEF components in Africa (de Sherbinin, 2014; Archer *et al.* 2018; Nkomo *et al.* 2006; Thornton *et al.* 2014). Furthermore, (i) the lack of coherent sub-regional plans, cooperative governance, and strategies for natural resource management, (ii) inadequate implementation, monitoring and evaluation of existing policies are contributing factors to the problems facing Africa.

Considering the mounting evidence of climate change impacts on the African continent, coupled with the growing population especially in East Africa (Agarwal *et al.* 2012), a cross-sectoral approach such as the WEF nexus is necessary to facilitate sustainable growth and development. There is a need for comprehensive analytical and socio-economic development tools that allow decision-makers to understand trade-offs and synergies of natural resource management. Such tools will contribute to prudent resource allocation, use and management. As a socio-ecological systems approach, the WEF nexus offers a sustainable solution to complex problems, such as climate change adaptation (Rasul, 2016, while still promoting economic development across different geographical areas.

It is worth pointing out that as WEF sectors are interconnected, so are the challenges facing the policies, conceptualisation, planning, implementation, and governance of the WEF nexus. As such, focusing on one sector of the nexus can potentially aggravate and/or transfer stress to another sector of the nexus (UNGA, 2015). Some of these challenges facing the WEF nexus include re-establishing suitable nexus governance and institutional structures/arrangements, bridging the science-policy interface, constructing institutional and human resource capacities for nexus-integrated planning and management, and incentivizing the private sector to invest in, and spearheading nexus-related projects (Leal Filho, 2018). Although the WEF nexus does have challenges, its adoption is crucial for Africa. This is because Africa has an abundance of natural resources, and this need to be managed for the benefit of African populations. Against this background, the adoption of the

WEF nexus approach would certainly help build resilient socio-economic systems, reduce duplication of efforts, improve resource mobilization, enhance institutional and human capacity, harmonize interventions, and manage and achieve the trade-offs that support sustainability (Van Eck *et al.* 2009).

The aim of this Chapter was to characterise efforts that have gone into understanding the WEF nexus and climate change adaptation in Africa. To that end, we aim to identify patterns of focus by various authors whilst identifying topics/themes that have received more attention between 1980 and 2021. The intention was to identify prominent areas from those that are still emerging to better identify gaps in the existing literature on the WEF nexus in Africa. The Chapter is structured in the following manner: we start by providing an outline of different nexus studies that have been done in Africa, this is followed by a bibliometric analysis used to assess the WEF nexus empirical research in Africa to elucidate the underlying intellectual patterns. In particular, the scientific mapping of the WEF nexus community includes trends, networks, keywords, and thematic analyses of intellectual performance. Furthermore, in this review, we examine different changes and adaptation strategies in WEF nexus studies in Africa.

2.2 VARIATIONS OF WEF STUDIES IN AFRICA

In this Chapter, we recognize that in Africa there have been several studies on the various combinations of the WEF nexus (Table 1), as different authors have viewed the WEF nexus from various perspectives. The variations of nexus studies that have been conducted in Africa include Food-Energy-Water (FEW/WEF) nexus (Ding *et al.* 2021; Ding *et al.* 2019; Ozturk, 2017; Naidoo *et al.* 2021; Liphadzi *et al.* 2021; Mabhaudhi *et al.* 2021; Mpandeli *et al.* 2020; Nhamo *et al.* 2020; Nhamo et al. 2020; Mabhaudhi *et al.* 2019; Simpson *et al.* 2019; Seeliger *et al.* 2018; Gulati *et al.* 2013); Energy-Water-Food-Waste and Sanitation (EWFWS) nexus (Nhamo *et al.* 2021); Water-Land-Food (WLF) nexus (Tantoh *et al.* 2015); Water-Energy-Food-Biodiversity-Health (WEFBH) nexus (Nhamo *et al.* 2021); Soil-Food-Water (SFW) nexus (Knight, 2021); Water-Energy (WE) nexus (Terrapon-Pfaff *et al.* 2021); Water-Energy-Climate Change (WECC) nexus (Mathetsa *et al.* 2019).

Our review of the literature showed that in Africa, WEF/FEW nexus studies contributed 68.6%, and the rest of the nexus variations contributed about 5.3% each. The major motivation drivers of change in nexus studies in Africa were climate change; increasing population; water, energy, and food insecurity; land degradation; biodiversity loss; urbanization; job and wealth creation; sustainable adaptation. Among these studies, climate change is a recurring driver of change in most of the nexus studies in Africa. It is important to put adaptation measures in place to prevent or minimize the impact of climate change and other drivers of change. In this review, various adaptation strategies were identified, which were not necessarily determined by the type of nexus but partly by what works well in different environments and partly by the policy in place. Adaptation strategies identified in some nexus studies on Africa include adaptative water, tariff programs, enabling environment, nexus planning, institutional arrangement, resource security, etc.

Table 2.1. Drivers of change and adaptation strategies in WEF nexus studies in Africa. Articles used in developing this table were randomly selected.

Authors	Adaptation Strategies	Type of Nexus	Drivers of Change	Variables
1. Ding *et al.* (2021)	- Adaptive water - Tariff programs	FEW Nexus Food-Energy-Water		Food: Agriculture Energy: Hydroelectric generation
2. Naidoo *et al.* (2021)	- Enabling environment - Institutional arrangements - Resource security - Equitable sustainable growth - Healthy environment	WEF Nexus Water-Energy-Food	- Water, energy, and food security - Sustainable adaptation - Job and wealth Creation	
3. Nhamo *et al.* (2021)	- Nexus Planning - Copping (reactive) adaptation - Incremental (Planned) adaptation - Transformational adaptation	Urban Nexus Energy-water-foodwaste And sanitation	- Climate change - Migration - Industrialization - Modernization - Globalization - Governance	Energy, water, food, and material provisioning systems.
4. Tantoh *et al.* (2021)		WLF Nexus Water-Land-Food	- Increasing population - urbanization - Increasing standards of living - Increasing demand for food	
5. Liphadzi *et al.* (2021)		WEF Nexus Water-Energy-Food		

Authors	Adaptation Strategies	Type of Nexus	Drivers of Change	Variables
6. Nhamo *et al.* (2021)	- Sustainability - Security - Governability - Scenario development - Technology and innovation - Policy strategy, laws and finance	WEFBH nexus Water-Energy-Food-Biodiversity-Health	- Climate change - Climate variability - Rise in economic growth - Population growth - Water population - Land degradation - Biodiversity loss - Ocean acidification	- Water: water security - Energy: energy security (CO2) - Food: food security (cereal) - Biodiversity: ecological security (forest) - Health: water, sanitation and hygiene
7. Mabhaudhi *et al.* (2021)	-Poverty reduction -Resilience & adaptation -Environment and human health	WEF Nexus Water-Energy-Food	Environmental Drivers - Climate change - Biodiversity loss - Sea level rise - Water & land Degradation Societal Changes - Population increase - Urbanisation - Globalisation - Dietary changes - Technology advancements	

Authors	Adaptation Strategies	Type of Nexus	Drivers of Change	Variables
8. Knight (2021)		SFW nexus Soil-Food-Water	- Climate change - Land degradation - Geological changes	Soil: Edaphic factor, geological factors Food: ecological and land-use factors, agronomy factors Water: socioeconomic and management factors, climatic factors
9. Mpandeli *et al.* (2020)		WEF nexus (Water-Energy-Food)	- Climate change - Population change - Environmental degradation - Political insecurity	
10. Terrapon-Pfaff *et al.* (2021)		WE nexus (Water-Energy)		- Water: Water quality - Energy: solar power plant
11. Nhamo *et al.* (2020) (a)	- Environment feedbacks - Socio-economic feedbacks	WEF Nexus Water-Energy-Food	- Climate change - Resource degradation - Biodiversity loss - Cultural change - Nutritional change - Population increases	
12. Nhamo *et al.* (2020) (b)		WEF Nexus Water-Energy-Food		

Authors	**Adaptation Strategies**	**Type of Nexus**	**Drivers of Change**	**Variables**
13. Mabhaudhi *et al.* (2019)	- Poverty reduction - Water, energy and food security - Increase resilience	WEF Nexus Water-Energy-Food	- Climate change - Socio-economic insecurities - Sea-level rise - Extreme weather events	
14. Mathetsa *et al.* (2019)		WECC Nexus Water-Energy-Climate change		- Water: water availability - Energy: hydropower, pump-storage, coal-generated electricity - Climate change: increased temperature, drought episodes
15. Simpson *et al.* (2019)	Nexus assessment	WEF Nexus Water-Energy-Food		
16. Ding *et al.* (2019)		FEW Nexus Food-Energy-Water		-Food: Agriculture -Energy: hydroelectric generation from reservoirs -Water: water use by urban residents, agricultural water use by vineyards
17. Seeliger *et al.* (2018)		WEF Nexus Water-Energy-Food		- Water: Breede river catchment - Energy: - Food: grapes, Fruit

Authors	**Adaptation Strategies**	**Type of Nexus**	**Drivers of Change**	**Variables**
18. Ozturk (2015)		FEW Nexus Food-Energy-Water		
19. Gulati *et al.* (2013)		WEF Nexus Water-Energy-Food	- Climate change - Population - Economic growth - Urbanization	- Water: water extraction, treatment, supply, desalination - Energy: biofuel - Food: Food quantity and quality, virtual water

2.3 MATERIALS AND METHODS

2.3.1 Focus area for review

Africa is the world's second-largest continent with a landmass of about 30.37 million km^2. Africa is exceptionally vulnerable to the impacts of climate change. This is because the average maximum temperatures in the whole of Africa are rising more rapidly than the global rate, and in some places, at twice the global rate of warming. The frequency and severity of droughts have increased in Africa since the 1970s, leading to land degradation and migration. Imminent rainfall variability is predicted to increase over most areas, with most models indicating fewer but higher amounts of rainfall events (Li and Zhao, 2015). Climate change affects the distribution, pattern, and intensity of rainfall with severe consequences for smallholder farmers and marginalized communities.

2.3.2 Materials

The databases that were used for this study were the Web of Science (WoS) and Scopus. WoS and Scopus are considered to have the largest collection of abstracts and citations of peer-reviewed scientific articles, books, and conference proceedings spanning a wide range of scientific disciplines, including science, technology, social sciences, medicine, and anthropology, among others. As such, bibliometric research has been extensively used from both WoS and Scopus resources (Salisbury, 2009). The use of both WoS and Scopus databases helped to include several topics, thus limiting the risk of not capturing certain documents in the field search (Cahlík *et al.* 2000; Lulewicz-Sas 2017). The following keywords were entered both in the Scopus and WoS web portals: "Water-Energy-Food nexus", OR "Food, Energy, Water nexus", AND "climate change", AND "adaptation", AND "vulnerability", AND "disaster", AND, "sensitivity", AND "Africa". These keywords were combined like "Water-Energy-Food nexus", AND "climate change", AND "adaptation", AND "Africa", we searched all the English-medium publications on Africa on WEF nexus plus climate change adaptation. Documents that were searched covered a period spanning four decades, from 1980-2021. Initially, 95 documents were retrieved from the WoS and Scopus core collection databases, but 30 duplicates were removed, and 65 documents were used. Table 2.2 gives a summary list of the documents retrieved, such as articles, book chapters, conference papers, reviews, etc.

Table 2.2 Documents considered in WEF nexus mapping.

Document Type	Number of Documents
Articles	42
Book Chapter	2
Conference Paper	1
Proceedings Paper	5
Review	15
Total	65

Note: The documents used in this research are not the only available documents on WEF nexus studies in Africa since this study used the ones available on the WoS and Scopus databases. Furthermore, keywords indicated earlier were searched based on the title of the documents, it is however possible to have some documents addressing WEF nexus in Africa, but the WEF concept is not indicated in the title of the documents.

2.3.3 Methods: Bibliometric Analysis

We used the bibliometric mapping technique on the 65 documents to analyze and visually represent the bibliographic data that were collected from the two databases. Bibliometric methods are statistical and mathematical (quantitative) methods that are used to analyze (scientific) publications. They map the process of publication, physiognomy, and the progress of knowledge within a research field (Aria *et al.* 2020). Bibliometric techniques can be utilized to categorize and quantify collaborations between journals, publications, authors, institutes, and countries, and they can also be used to assess their contribution to definite topics (Li and Zhao, 2015). The bibliometric techniques could be logical at stages of titles, keyword lists, publications summaries, or even the entire citation records to salvage the definite topics and subject categories assigned to publications (Salisbury, 2009). In addition to demonstrating the diversity of research themes, the co-occurrence of keywords recognizes the multidisciplinary nature and potential directions (sub-areas/areas) for further advancement of a field (Simpson *et al.* 2019) It allows researchers to identify the leading topics, latest advancements, and existing gaps in a certain area of a research discipline vividly and graphically (WWF SABMiller, 2014). Various authors have used it to support their decision-making processes (Lulewicz-Sas, 2017).

The use of the bibliometric mapping technique was undertaken in this study to visually represent scientific information by using bibliographic data, which was carried out using quantitative approaches (Aria, 2020). Based on the bibliometric R software package (Alahacoon *et al.* 2022). The WEF nexus information was analyzed, whereas bibliometric network maps were developed using VOSviewer (i.e. Visualization of Similarities) (Cahlík, 2000). In this research, the bibliometric analysis focused on the overall intellectual structure of the WEF nexus through the lens of climate change adaptation during the selected study period (1980-2021). A set of analyses that included analyzing the annual production of scientific publications, the most productive countries and their collaborations, keyword occurrence, and thematic progression of research were conducted.

2.4. RESULTS

2.4.1. Publications on WEF Nexus in Africa

Figure 1.1 displays countries that carried out studies on WEF nexus in Africa only or African countries (Single Country Publications (SCP)), and those studies which focus on Africa or African countries along with other countries (Multiple Country Publications (MCP)) from 1980-2021. According to Figure 2.1, the top 6 most productive countries in the production of WEF nexus articles are South Africa, the United Kingdom, the USA, Germany, Kenya and Zimbabwe. Figure 1 shows that South Africa is the country with the highest number of published articles with 19 publications, 10 of which were published under single country multi-country collaborations and 9 through multi-country collaborations. With 11 publications, the United Kingdom and the USA rank second with 5 and 8 single-country publications, respectively, and 6 and multi-country publications respectively. It is important to note that the ranking of countries depends on the affiliation of the main author at the time of publication.

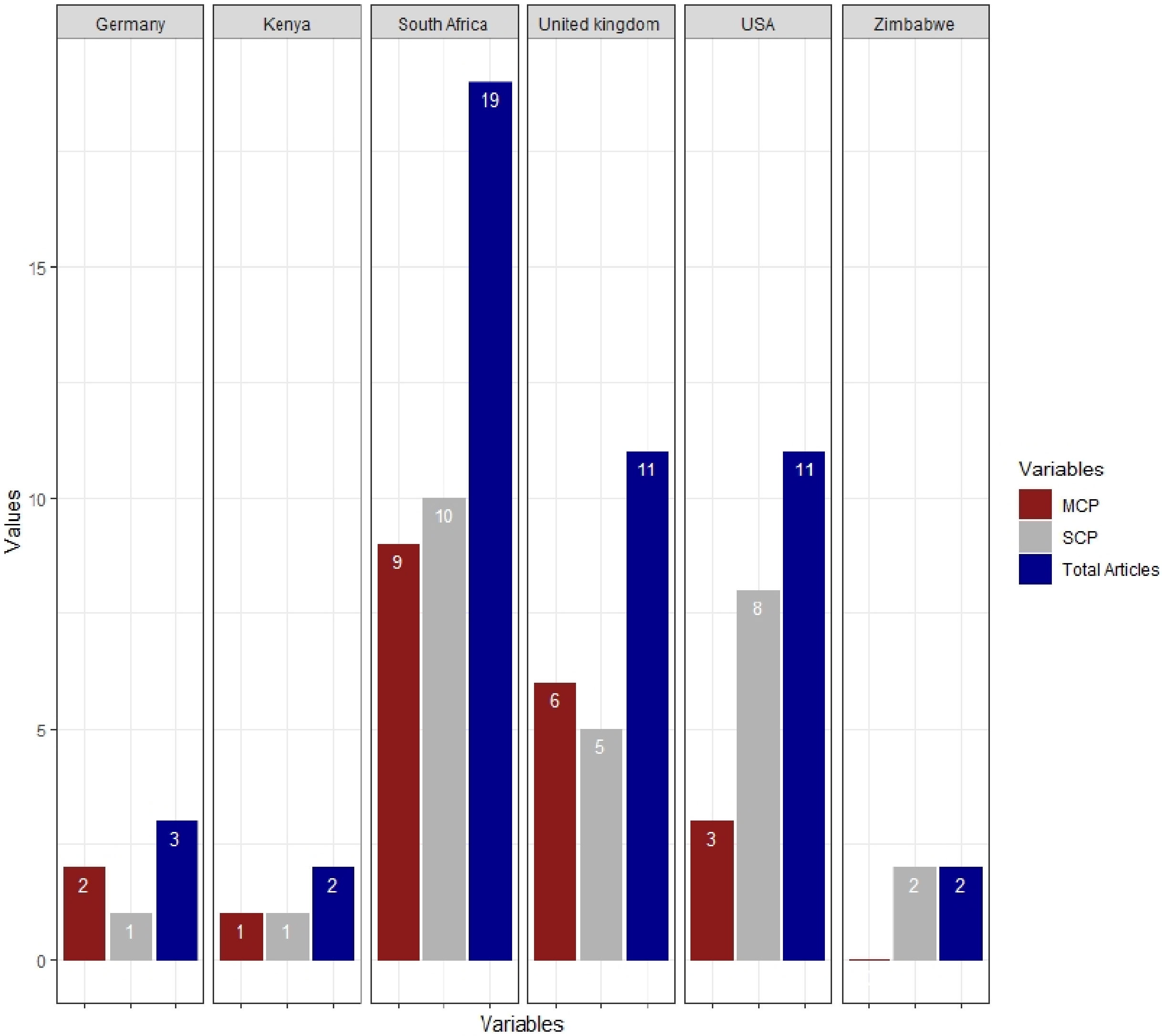


Figure 2.1: Top 6 Most productive countries in research on climate change adaptation through the lens of WEF nexus in Africa (1980-2021). Multiple Country Publications (MCP), Single Country Publications (SCP).

2.4.2. Trends in Publications of WEF Nexus in the World, Africa and South Africa

Figure 2.2 illustrates the temporal and geographic distribution of articles published in Scopus and WoS in the World (976 documents were used), Africa (65 documents were used) and South Africa (18 documents were used) from 1980-2021 on WEF nexus and climate change adaptation. Globally, studies on the WEF nexus started as far back as 2007 (Figure 2.2A), with a considerable rise in the number of studies starting in 2013. From the year 2015 to date, there has been a continuous rise in the annual publications on WEF nexus worldwide. The annual percentage growth rate of nexus studies at the global level is 44.68% for the period 1980 to 2021.

Our results showed that research into the WEF nexus in Africa began to emerge in 2008. Similar to the trend observed in global publications on the WEF nexus, Africa displayed a considerable increase in WEF nexus publications from 2008 to 2021, as demonstrated by an overall growth rate of approximately 23.16% in scientific publications each year. However, in contrast to the relatively smooth increase in global publications, WEF nexus publications in Africa show year-to-year fluctuations.

WEF nexus studies conducted in South Africa began in 2013, and their temporal distribution shows a pattern that is similar to that of Africa (Figure 2.2C). From 2016 to 2021, there has been a considerable rise in the number of publications produced in South Africa (Figure 2.2C). The annual growth rate of nexus studies in South Africa for the period 1980 to 2021 is 18.92%.

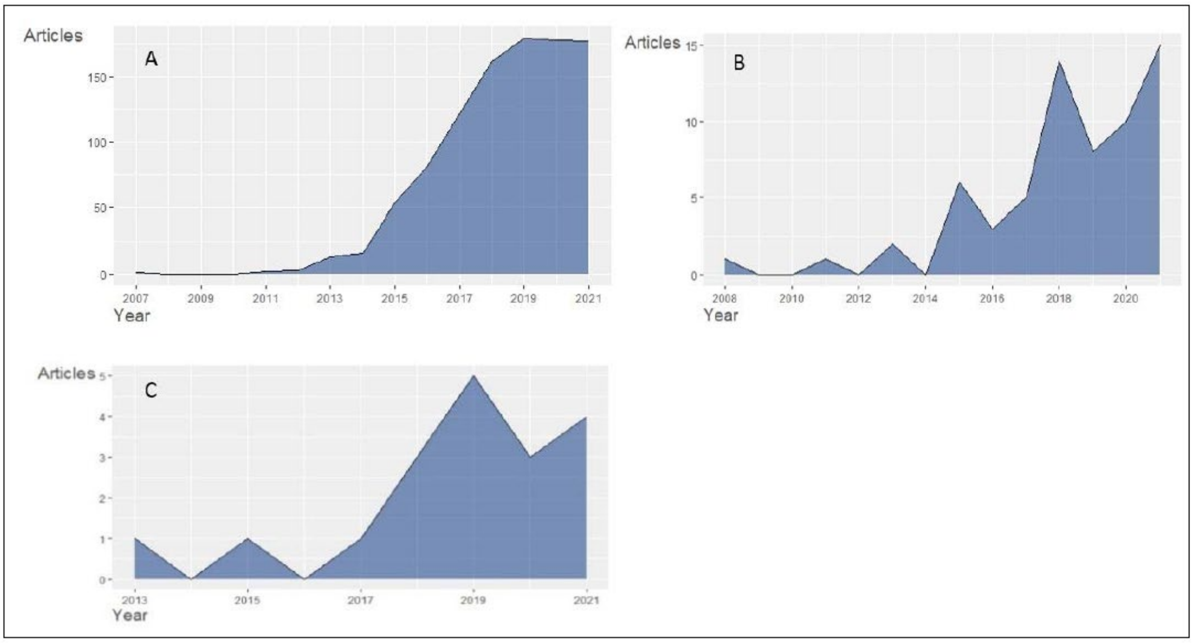


Figure 2.2: Annual distribution of publications published in (A) Global, (B) Africa and (C) South Africa.

It is worth noting that there is a huge difference in the number of studies published in the World compared to those published in Africa in the period considered for this study (1980-2021). In that period, hundreds of publications were published in the World, while far less than that were published in Africa. This considerable difference in the number of publications is evident despite a relatively similar period of starting to publish on the WEF nexus between the World (2007) and Africa (2008) (Figure 2.2A, B).

This is evident in Figure 2.2, where Figure 2A shows that global studies could be as high as 180 publications a year (this was recorded in 2018), while the highest number of recorded articles for Africa was 14 publications a year (also in the year 2018 (Figure 2.2B, y-axes). South Africa is the highest producer of WEF nexus publications in Africa, with 5 publications a year (Figure 2.2C y-axis).

2.4.3. Analysis of Keywords

In Figure 2.3, the co-keyword network shows three distinct clusters from 100 top keywords having a total of 3656 links. Each cluster characterized a subfield of the field of WEF nexus. Suitable labels for the three most important clusters could be allotted to each of them by analyzing its main node circles. Within each cluster, different sizes of circles were used to represent the frequency that each keyword was used in the 65 analysed publications. For example, a large circle indicates that the keyword has been used more frequently in the publications. The topic similarity and relative strength of the two keywords were demonstrated by their distance from each other.

Keywords have been extracted from the titles or abstracts of the 65 analysed publications. (these are the author's keywords) and were grouped into 3 clusters (red, green and blue) using a strength association methodology. The circles with the same colour suggested a similar topic among the publications. The red cluster represents keywords that are related to the application of the WEF nexus. The green cluster represents keywords that are related to the implementation of the WEF nexus, while the blue cluster represents keywords that are related to the implications of the WEF nexus (Table 2.3).

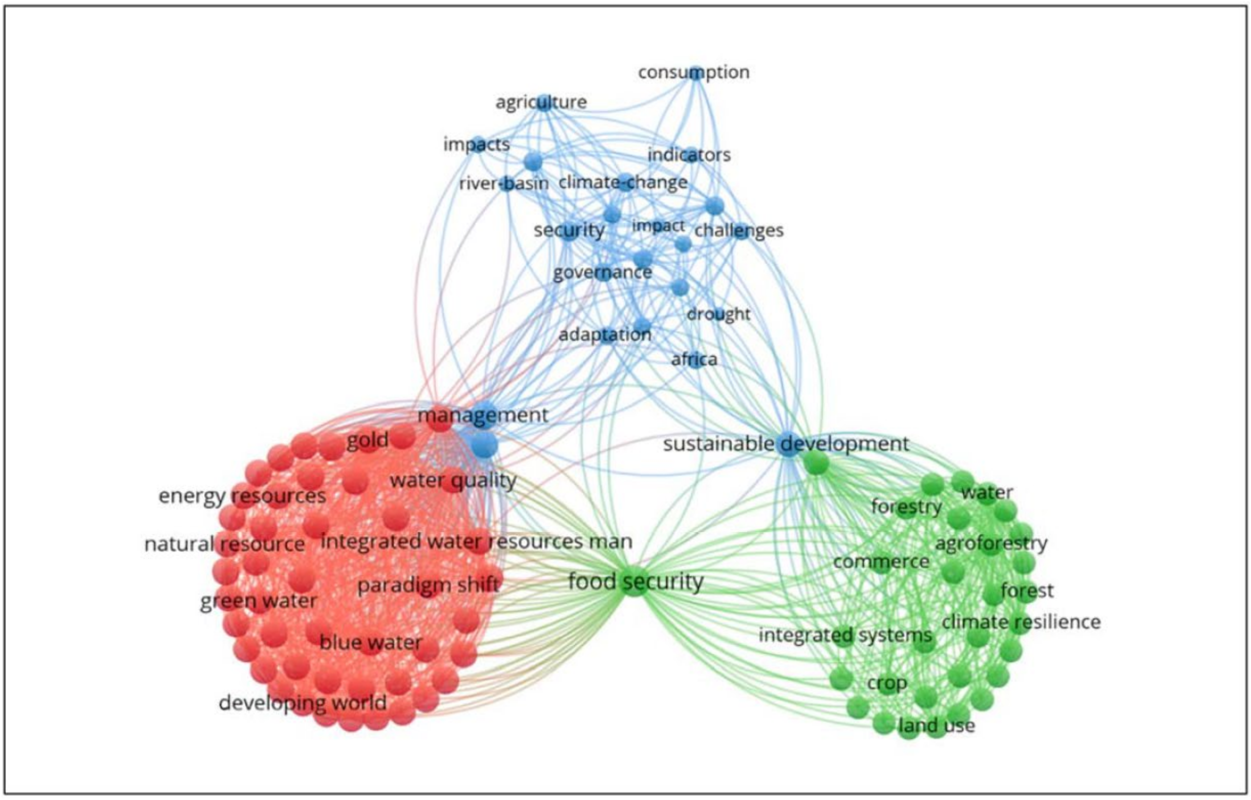


Figure 2.3: Top 100 Keywords used in publications that link Water-Energy-Food nexus with climate change adaptation from 1980-2021. Man = Management. Red cluster represents keywords that are related to the application of the WEF nexus; Green cluster represent keywords that are related to the implementation of the WEF nexus; and blue cluster represent keywords that are related to the implications of the WEF nexus.

Table 2.3. Clusters and their key messages.

Clusters	Links	Key Messages from Figure 3
Red	2223	Application of WEF nexus
Green	1023	Implementation of WEF nexus
Blue	410	Implication of the WEF nexus

From the 65 articles that were analysed, we found a total of 3656 links between the top 100 keywords (Table 2.3). The largest number of links between the top 100 keywords were found in topics on the application of WEF nexus, and these were almost five-fold higher than those on the implication of WEF nexus (Table 2.3).

Figure 2.3 shows the top 100 keywords used in publications that link Water-Energy-Food nexus with climate change adaptation from 1980 to 2021 for Africa. The results show that 46 keywords fall under the red cluster (application of WEF nexus), while the green cluster (implementation of WEF nexus) contained 31 keywords and the blue cluster (implication of WEF nexus) showed 23 keywords (Figure 2.3).

2.4.4. Thematic Progression Analysis

An approach that was used in bibliometrics to explore the conceptual structure of a given research area is called thematic analysis (Corte *et al.* 2019). With this approach, it is possible to create graphical representations containing a summary of the main points in a body text. Moreover, the extracted topics could be classified according to their structure and role within the network. Thematic mapping allows four different typologies of themes to be visualized, as shown in Figure 4.4. A thematic map is developed using the Keywords Plus field (Aria *et al.* 2022). During this process, the title of all references is reviewed and highlights additional relevant but overlooked keywords that were not listed by the authors. Keywords Plus is normalized differently from the author's keywords. An article's content can be captured with greater depth and variety using Keywords Plus terms. Each theme quadrant is organized following its centrality and density rank value, as well as vertical and horizontal centrality and density (Cahlík, 2000). Spheres (circles) have dimensions proportional to the number of documents that correspond to each keyword in each quadrant.

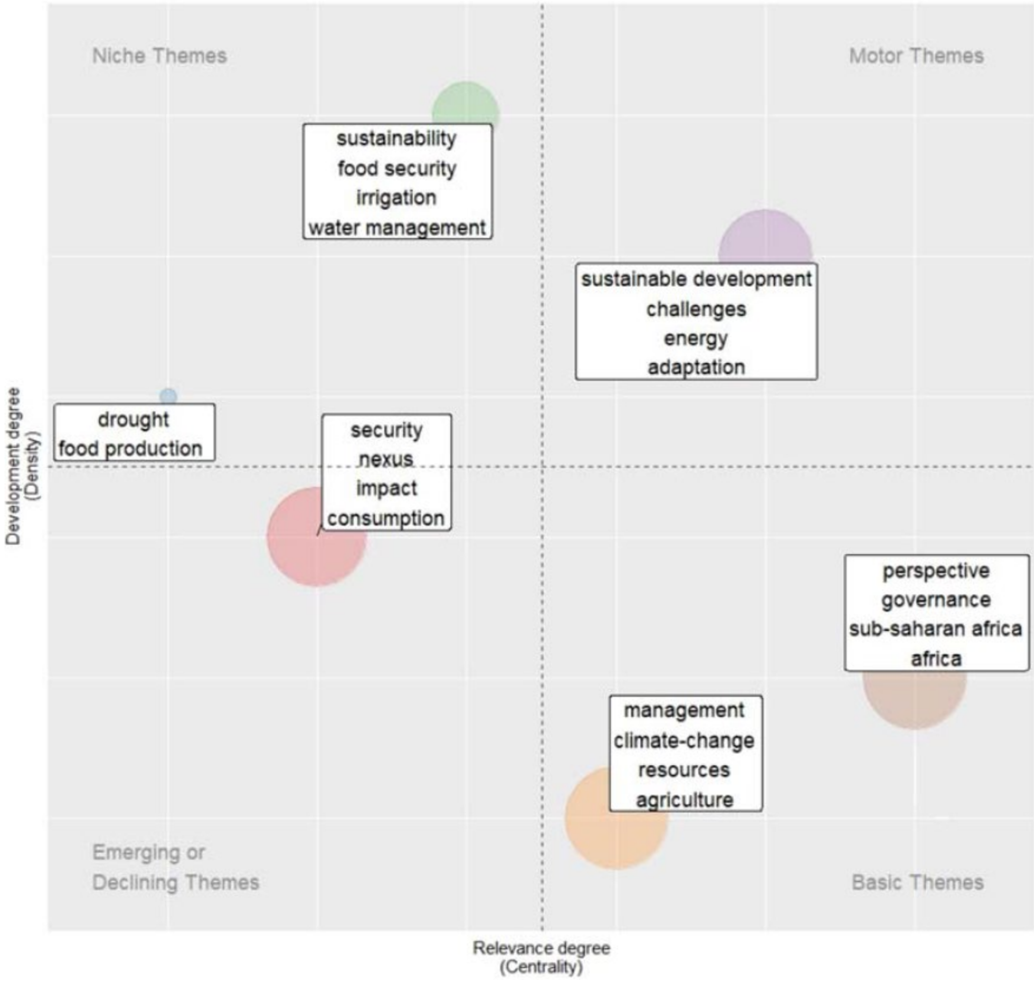


Figure 2.4: Thematic progress of WEF nexus research in Africa. Located in the Upper-right quadrant are the motor themes; located in the upper-left quadrant is the niche theme; located in the lower-left quadrant is the emerging themes and located in the lower-right quadrant is the basic themes.

The motor themes or hot topics appear in the upper-right quadrant (Figure 4) (Alahacoon *et al.* 2022). They are distinguished by values that have both high centrality and high density (Table 2.4). They are well established and appropriate for structuring the conceptual framework of the field of WEF nexus in Africa. Motor themes for this analysis contain seven themes (Table 2.5). The most recurring words associated with the cluster sustainability development for the period of this study were “challenges”, “energy”, and “adaptation (Figure 2.4).

Table 2.4. Centrality and density of themes in WEF nexus in Africa.

	Centrality	Density	R Centrality	R Density	Label	Color	Name	Themes
1	6.65	193.49	2	3	1	Rose	security	Emerging or declining theme
2	1.10	220.83	1	4	2	Blue	drought	Niche theme
3	8.36	619.10	3	6	3	Green	sustainability	Niche theme
4	11.13	289.28	5	5	4	Violet	Sustainable development	Motor Theme
5	9.12	126.46	4	1	5	Orange	management	Basic theme
6	14.90	191.17	6	2	6	Brown	perspective	Basic theme

Table 2.5. The four themes identified by the thematic analysis from WEF nexus publications (1980-2020) in Africa and the most recurring words in each theme.

Motor Themes (Well Established	**Niche Themes (Strongly Developed but Still Marginal)**	**Emerging or Declining Themes (Not Fully Developed or Marginally Interesting)**	**Basic and Transversal Themes (Significant and Cut across Different Areas of the Nexus)**
Sustainability development	Sustainability	Security	Management
Challenges	Food security	Nexus	Climate change
Energy	Irrigation	Impact	Resource
Adaptation	Water management	Consumption	Agriculture
Food nexus	Integrated water resource management	Emissions	Impacts
Land use	Drought	Poverty	Basin
Indicators	Food production		Land
			Rainfall
			Perspective
			Governance
			sub-Saharan Africa
			Africa
			Analytic hierarchy process
			Policy
			River
			Vulnerability

Located in the upper-left quadrant are the niche themes (Figure 2.4) (Alahacoon *et al.* 2022). They have a lower value of centrality and higher values of density (Table 2.4). They are strongly developed but still marginal in the field of WEF nexus in Africa. The niche themes in this analysis contained seven themes, as presented in Table 2.5. The niche themes quadrant contains two main clusters, as displayed in Figure 2.4. The most recurring words connected to the sustainability cluster for the period of this study were “food security”, “irrigation”, and “water management” (Figure 2.4). The most recurring word associated with the cluster drought is “food production”.

In the lower-left quadrant are the emerging or declining themes (peripheral topics (Figure 2.4) (Alahacoon *et al.* 2022). They have lower values of centrality and density (Table 2.4). They are not fully developed or marginally interesting for the field of WEF nexus in Africa. The emerging or declining themes for this study are six themes (Table 2.5). The most recurring words connected to the security cluster for the period of this study were “nexus”, “impact”, and “consumption” (Figure 2.4).

Finally, the lower-right quadrant shows the themes that are basic and transversal (Figure 2.4) (Alahacoon *et al.* 2022). They have higher values of centrality and lower values of density (Table 2.5). These are themes that are significant to the field of WEF nexus in Africa and cut across its different areas. The basic themes for this study contain 16 themes (Table 2.5). The most recurring words associated with cluster management for the period of this study were “climate change”, “resources”, and “agriculture” (Figure 2.4). While the most recurring words connected to the cluster perspective for the period of this study were “governance”, “sub-Saharan Africa”, and “Africa”.

2.5. DISCUSSION

This study focused on progress made to understand the WEF nexus using Scopus and Web of Science publications for the period 1980 to 2021, with Africa as the case study. According to this review, researchers have explored different combinations of the WEF nexus in Africa (see Table 2.1). Our results indicate that the WEF combination remains by far the most dominant combination among the nexus publications; as more than half of the studies (52.8%) used the WEF combination, followed by the FEW combinations with 15.8% and the rest of the various combinations contributing 5.3% each. This is in line with the work of Keairns *et al.* (2016), who concluded that the WEF nexus is rapidly expanding among scholarly literature. Globally and in Africa, WEF nexus studies are relatively new as the first publications occurred in 2007 and 2008 in Africa. This pattern may reflect the emergence of systems thinking in the treatment of sustainability issues in literature. Our results that South Africa has the highest number of publications on the WEF nexus in Africa, this result is similar to that of Botai *et al.* (2021). These results are encouraging as South Africa has committed to addressing what it refers to as the country’s ‘triple challenge’—poverty, inequality, and unemployment—by the year 2030. These challenges are of course intricately linked with the WEF concept. That said, the driver for the high number of publications on the WEF nexus in South Africa is not obvious. It is likely that this pattern was caused by the availability of funds to conduct research in this field. Funding for research has been highlighted as one of the limiting factors to focus and sustaining research efforts (Botai *et al.* 2021); Nhamo *et al.* 2020).

According to the trend analysis for publications on the WEF nexus in this study, the annual growth rate of the WEF nexus globally is 44.7%, 23.2% in Africa and 18.9% in South Africa. However, there is a high disparity in the number of annual WEF publications in the World (180 articles annually), Africa (14 articles annually) and South Africa (five articles annually). Both results, the percent annual increase of publications and the total number of annual publications on the WEF nexus should challenge researchers in Africa and on Africa to invest more effort in publishing in this field to inform decision-makers that are grappling with the provision of these basic needs to the communities. More information on the WEF may increase awareness about the WEF concept, and that may contribute to breaking down the inertia of African decision-makers in effective investment in these sectors for the benefit of African communities.

Climate change impacts on the WEF nexus at national and continental levels are multilayered. Breaking down keywords from WEF nexus publications that link the WEF nexus with climate change adaptation in Africa was divided into three broad aspects: application of WEF nexus, implementation of WEF nexus and implication of the WEF nexus. Our results showed that the research on the WEF nexus in Africa has focused on the application aspects of the nexus, followed by the implementation aspects of the nexus. In our view, this is an important finding as the focus on the application and implementation of the WEF nexus considering the changing climate shows that researchers are grappling with approaches for translating the conceptual underpinnings of the WEF nexus to solutions for improving the lives of African communities.

The four themes obtained from the thematic progression analysis of concepts of the WEF nexus proved very useful to understand the scope, the focus and the gaps in the literature that addresses the WEF nexus in Africa. It is worth noting that the water component of the WEF nexus is absent among the most recurring words in the theme on well-established concepts and is appropriate for structuring the conceptual framework of the field of WEF nexus in Africa. While the energy component of the WEF nexus is absent among the most recurring words in two themes, that on strongly developed concepts but still marginal for the field of WEF nexus in Africa and on the basic and transversal theme. This pattern suggests that research on the WEF nexus in Africa rarely places equal focus and balances all three components of the WEF nexus.

2.6. CONCLUSIONS

According to the NIC (National Intelligence Council (NIC), 2012), WWF and SABMiller (WWF SABMiller 2014), the population of Africa is on the increase, and the demand for water, energy and food will continue to increase. Alahacoon *et al.* (2022) showed that in the northern and central regions of Africa, rainfall has increased statistically significantly, while the Southern and Eastern regions of Africa did not experience any statistically significant changes in rainfall. Moreover, according to FAO (2020) there is an increase in the undernourished population in Africa as such, food security in the continent is not improving. Meanwhile, according to a global dashboard dedicated to registering progress on energy access across Africa known as Tracking SDG7: The Energy Progress Report, which was last updated in 2019, the African continent currently has the worst electricity access in the world. A study by Moussa *et al.* (2019) showed that population growth has outpaced growth in electrification in recent decades, leading to an increase in the number of people without electricity, this study revealed that more than 60% of the African population does not have access to electricity.

From this study, it is evident that Africa needs to sustain and improve the momentum of publications on all three components of the WEF nexus. This study did not look at the dissemination of results from research on the WEF nexus. Access to the results of this research by civil society and decision-makers may assist in designing and developing solutions to enable the implementation of the WEF concept to improve the lives and livelihoods of African communities. From this study, we can conclude that there is a need for:

- more studies on the WEF nexus in Africa,
- these studies should focus more on the application or practice of WEF nexus considering the impacts of climate change,
- detailed studies to balance under-represented concepts as shown in the thematic progression analysis of concepts of the WEF nexus in this study.

African governments, African civil society organisations, academia, the private sector and international partners that work in Africa should pay attention to information that comes from WEF studies and make use of the suggested solutions as Africa advance its efforts towards sustainable development.

CHAPTER 3: METHODOLOGY

3.1 STUDY AREA: BACKGROUND INFORMATION AND LOCATION OF THE MPUMALANGA PROVINCE

Mpumalanga basically translates as “the place where the sun rises”. It is located in the northeast of South Africa and is accounting for 6,5% (79490 km^2) of South Africa’s land surface area (Statistics, 2006). The Mpumalanga province is the second smallest in South Africa and the country’s fourth-largest economic contributor. The provincial headquarters are at Mbombela (previously known as Nelspruit). It is bordered on south by the Free State and KwaZulu-Natal, on the West by Gauteng, on the north by Limpopo and on the east by Swaziland and Mozambique (Eggink, 2015) (Figure 3.1). It is made up of 18 local municipalities and 3 district municipalities (Stats SA, 2014) (Table 3.1).

Table 3.1: District and local municipalities in the Mpumalanga Province.

	District municipalities		
Local municipalities	**Ehlanzeni District**	**Nkangala District**	**Gert Sibande**
	Thaba Chweu	Victor Khanye	Chief Albert Luthuli
	Bushbuckridge	Emalahleni	Msukaligwa
	Nkomazi	Steve Tshwete	Mkhondo
	City of Mbombela	Emakhazeni	Dr Pixley Ka Isaka Seme
	Umjindi	Thembisile Hani	Lekwa
		Dr JS Moroka	Dipaleseng
			Govan Mbeki

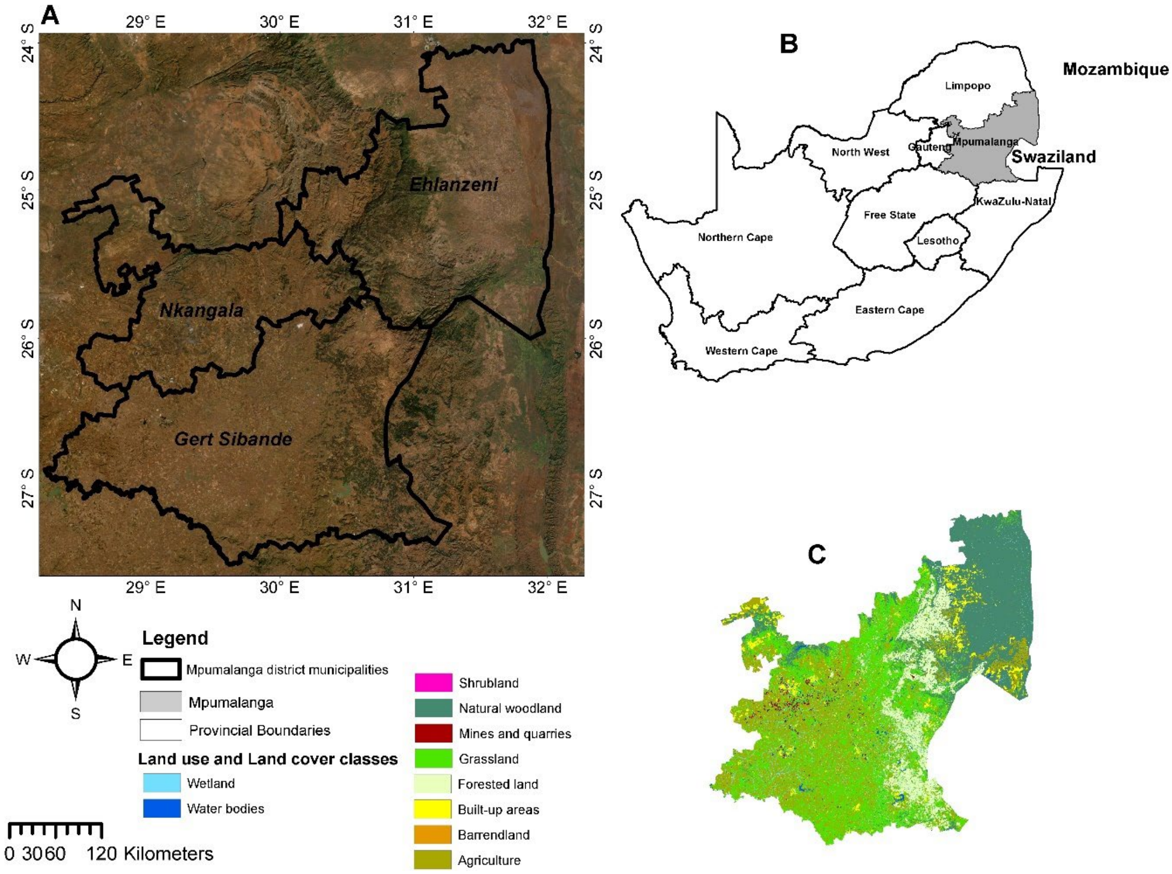


Figure 3.1: Location of the study area. (A) District municipal boundaries in Mpumalanga. (B) Mpumalanga province relative to other provinces in South Africa. (C) Dominant land cover and land use activities in Mpumalanga province.

3.1.1 Geology, topography, and landscapes

The Mpumalanga province is characterized by its extensive agricultural fields, remarkable mining and industry, picturesque landscapes, wildlife, and vegetation. The Mpumalanga Escarpment, with its variety of geology and landforms, is one of the Great Escarpments of South Africa (Viljoen, 2015). Two of the world's most important geological formations are in the Mpumalanga Province: the Witwatersrand Supergroup (gold ore resources) and the Bushveld Complex (platinum group of minerals) (Groenewald and Groenewald, 2014). The 1870 gold rush period can be seen in Barberton and Pilgrims Rest, which has been declared a national monument (Harrison, 2004). Another feature of this province is some of the earth's natural oldest rock formations. Particularly, the Barberton Makhonjwa Mountains and crocodile river mountains, which are home to metamorphosed granite and old greenstones. In 2018, the Barberton Makhonjwa Mountain was recognized as a natural world heritage site, increasing the pride in the Mpumalanga’s endearing features (Barberton, 2022). It has the oldest cave system in the whole world and is interbedded by sedimentary rock and African cratonic Basement rocks. Figure 3.2 showing the geology of the Mpumalanga province.

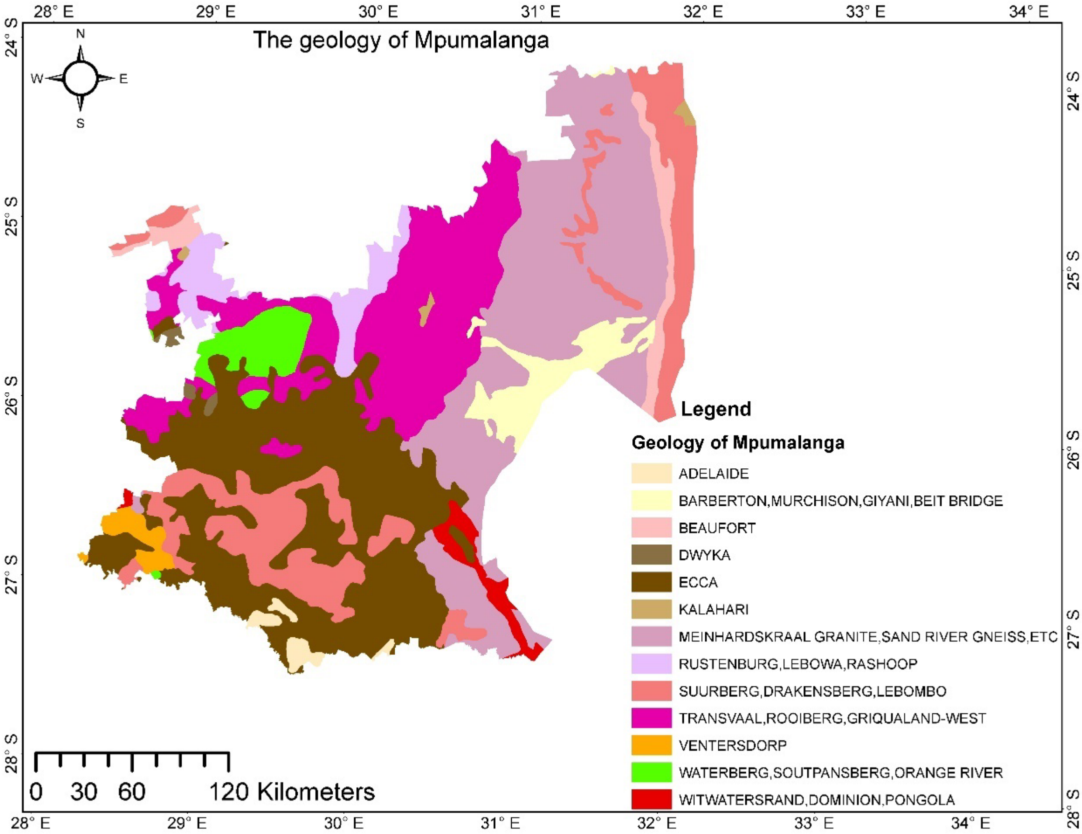


Figure 3.2: The geology of Mpumalanga.

The Mpumalanga province is divided into two halves by the Drakensberg Escarpment: the easterly low altitude subtropical lowveld and the westerly high-altitude grasslands of the highveld (see Figure 3.4). The Highveld stretches for hundreds of kilometres eastwards until it reaches the Escarpment in the north-east, where it plunges down to the Lowveld (Mpumalanga agricultural education and training report). Figure 3.3 is showing the topographic characteristics of the Mpumalanga province.

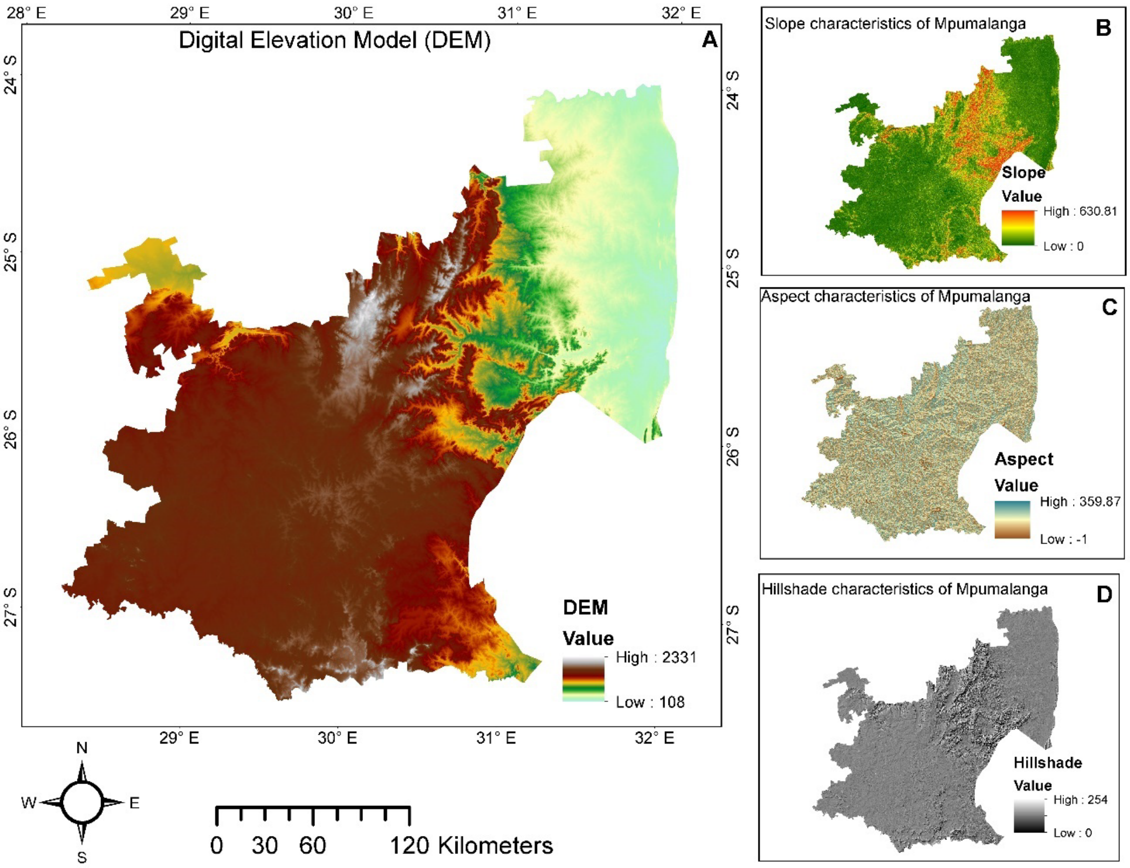


Figure 3.3: Topographic information of the study area derived from the Digital Elevation Model (DEM) (30 metres). (A)Digital elevation Model (DEM), (B) slope, (C) aspect and (D) Hill shade.

3.1.2 Main vegetation types of biomes in the study area

Mpumalanga province is well known for its distinctive and significant biodiversity. In Mpumalanga, there are three different types of biomes: grassland, savanna, and forest (Figure 3.3). The grassland biome, which makes up most of the province, is found in the central highveld and escarpment areas (on south and east-facing slopes and in river valleys) (MTPA, 2014). While it is vital for biodiversity, the grassland biome is the least well-protected of Mpumalanga's biomes and is therefore threatened by rapid land use changes. Figure 3.4 shows the locations of protected areas in the province of Mpumalanga.

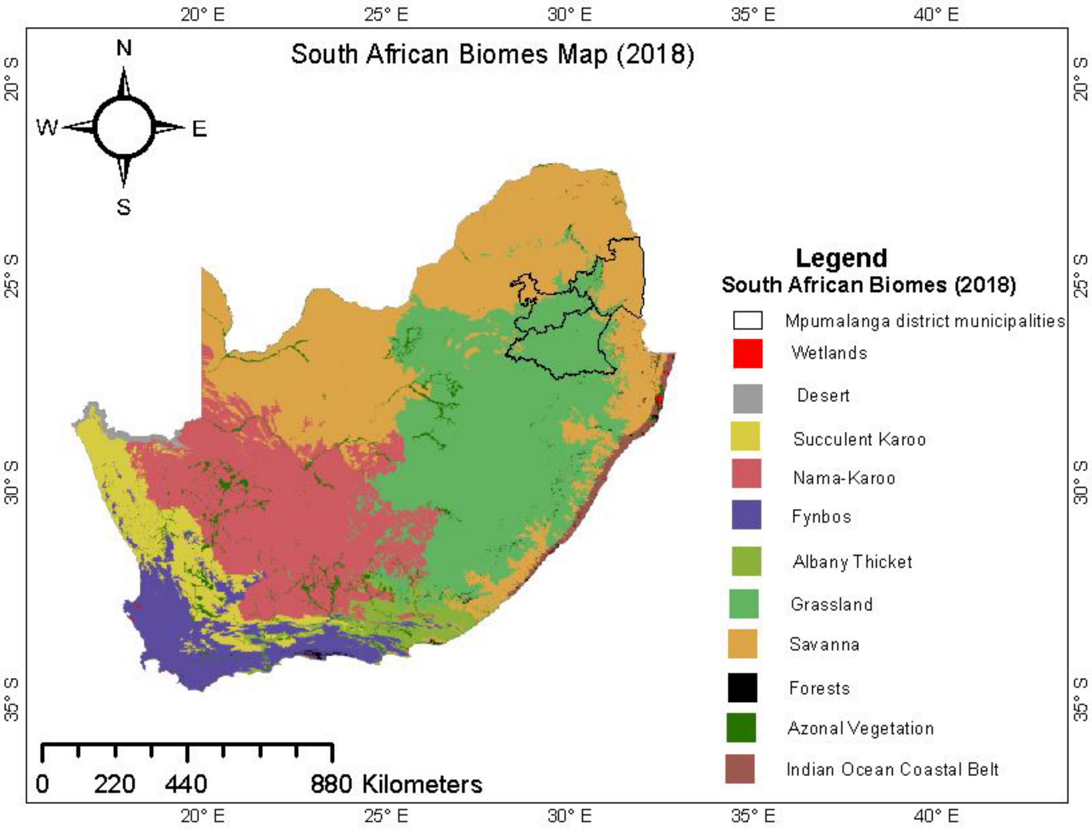


Figure 3.4: South African vegetation Biome map.

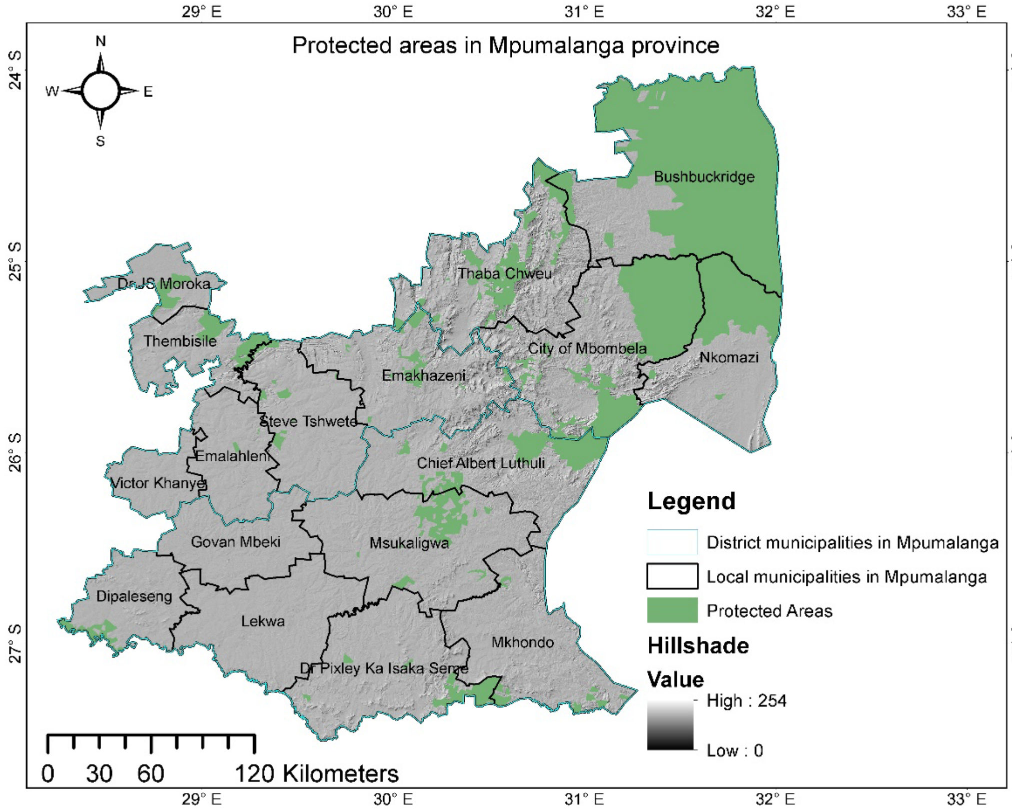


Figure 3.5: Location of protected areas in Mpumalanga.

3.1.3 The water supply situation in the study area

Groundwater, rainfall and rivers are the primary sources of water supply in the study area. Most of the water that runs through this region is used for agriculture and mining operations. Rivers and dams allow for the formation of landscapes like the Blyde River Canyon, the Kadishi Tufa waterfalls, and Berlin Falls. The primary rivers are the Vaal, Olifants, Nkomati, Crocodile and Usuthu. The Inkomati-Usuthu WMA, the Olifants, and the Vaal are the three Water Management Areas (WMA) that traverse provincial boundaries (Figure 3.6).

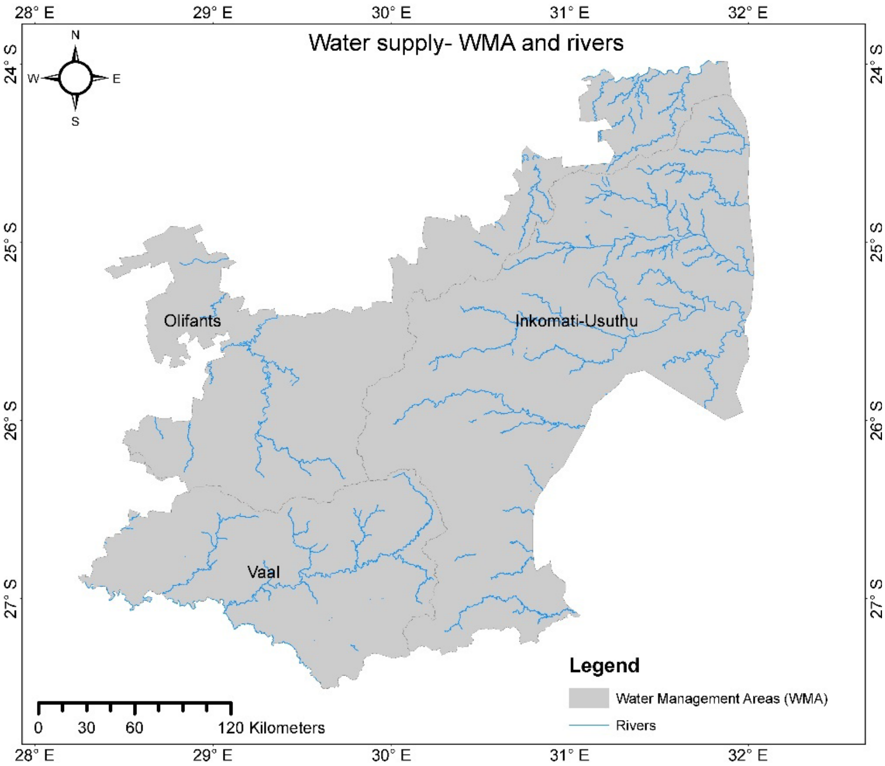


Figure 3.6: water management areas and rivers

3.1.4 Climate conditions in Mpumalanga

The study area has a varied climate. This province is located in a section of South Africa where the bulk of rain falls during the summer (Adisa, 2018). The escarpment divides the area of summer rainfall into Lowveld and Highveld, with the Lowveld having pleasant winters and a subtropical climate and the Highveld has freezing winters with little or no rain and hot, humid summers. Mpumalanga receives between 500 and 800 mm of rain annually (Adisa, 2018). According to Kapwata (2015), humidity in Southern Africa is lowest in the winter and highest in the summer. Summer temperatures in Mpumalanga range from 20°C to 38°C, with the greatest summer maximum temperature of 48°C (Kapwata, 2015). Temperature in the winter ranges from 6°C to 20°C (Benhin, 2006). Figure 3.8 presents monthly climate and climatic water balance for Mpumalanga from 1990 to 2020.

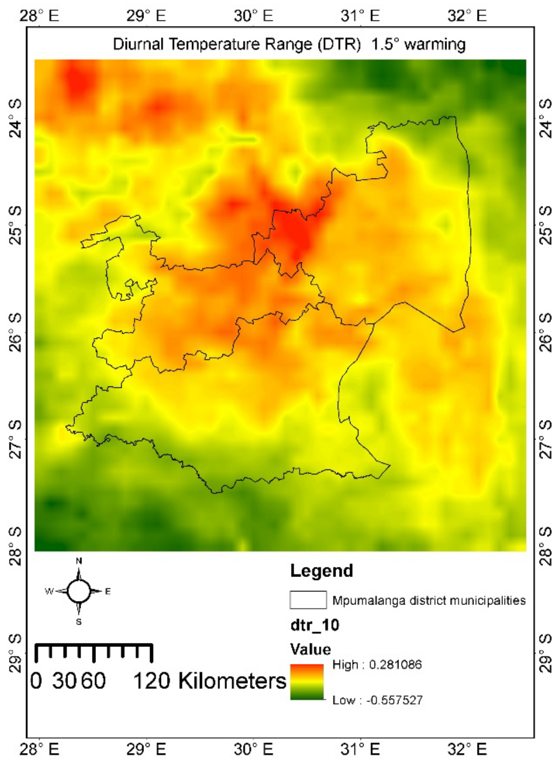


Figure 3.7: Diurnal temperature range (in °C) relative to that of 1961-1990 for the 1.5.

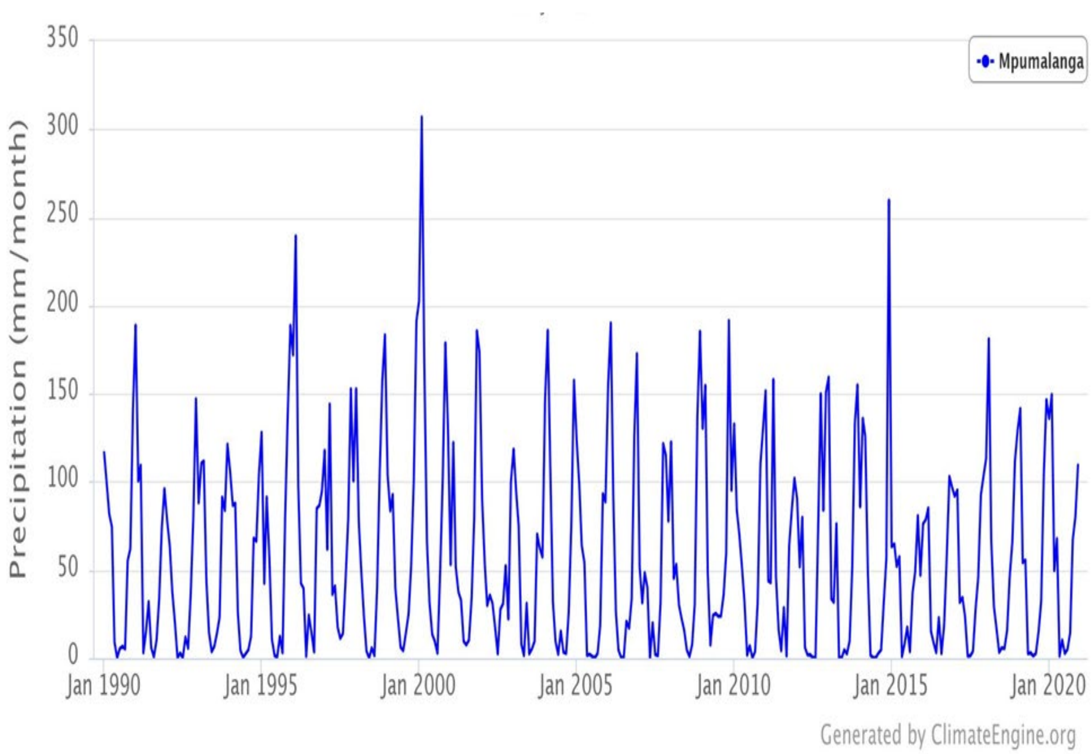


Figure 3.8: Terra climate average precipitation (1990-2020).

3.1.5 Livelihood conditions

The natural resources of Mpumalanga are being impacted by socioeconomic changes. Social development focuses on improving the well-being of every individual in society so they can reach their full potential which is impacted by aspects such poverty, education, health, secure and safe environment (van Breda, 2018; Patel and Hochfeld, 2013). Economic development refers to the change of a country's economy to increase Gross Domestic Product (GDP), employment and income (Panth, 2021). Most of the Mpumalanga's population, especially the poor, reside in low-income places, but they continue to move to high-income areas like Witbank-Middleburg, Nelspruit (Mbombela)-White River, and Secunda and its surroundings. The Mpumalanga province has an excellent road and rail infrastructure, making it easily accessible and promoting commercial and industrial development. Agricultural sector is critical in the battle against poverty and ensuring food security for Mpumalanga residents. The province’s varied landscape makes it feasible to grow a wide range of crops. The Lowveld is known for citrus and subtropical fruit, whereas the Highveld is known for summer cereals like maize and grain sorghum while most of the hills on the escarpment are covered in exotic plants and plantations such as gum and wattles. Due to the variety of available resources, special economic zones have emerged, most notably the development of heavy industrial activity including power plants, steel mills, and chemical facilities (Province, 2013).

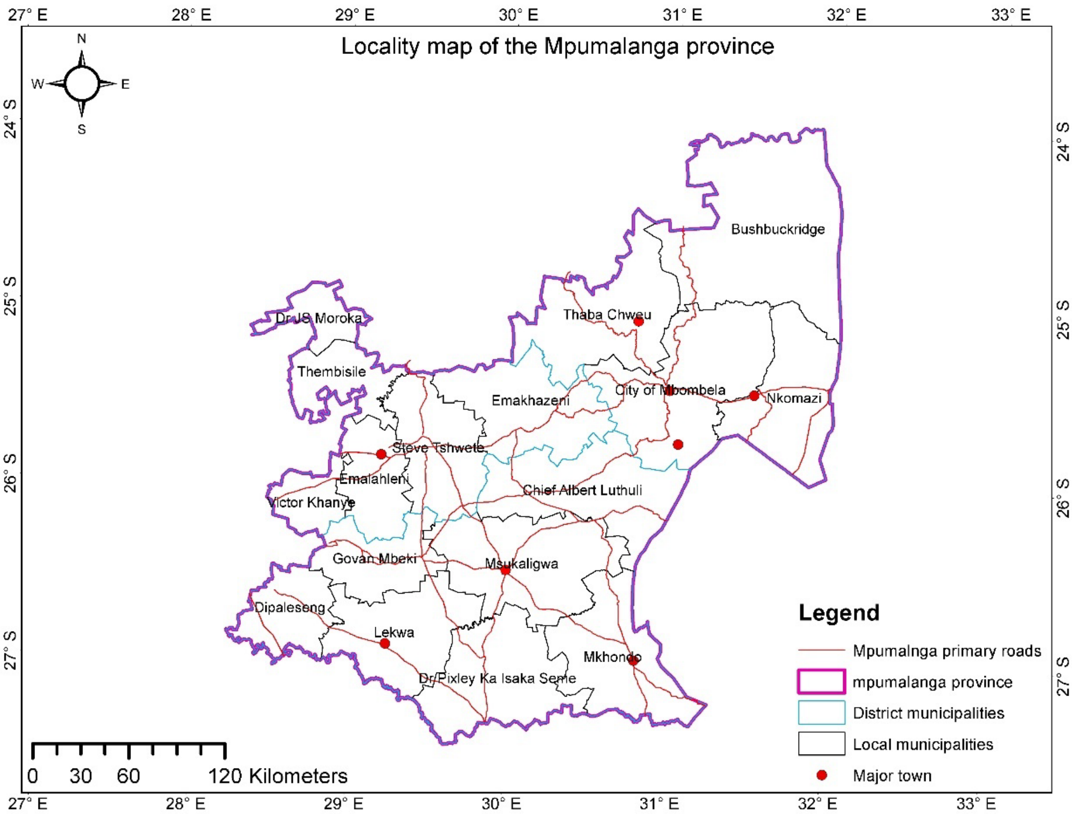


Figure 3.9: Locality map of the Mpumalanga province.

3.2 UPDATING THE NATIONAL CLIMATE CHANGE RESPONSE DATABASE

The current study successfully supported updating the National Climate Change Response Database (NCCRD) by cleaning, and uploading the climate change adaptation projects and programmes (https://nccrd.environment.gov.za/submissions/new/CA35433E-F36B-1410-8684-00528B626FB9). About 141 projects and programmes that focused on adaptation were added to the database and mapped according to the local municipalities of Mpumalanga province. The collected climate change adaptation projects were submitted to DFFE for review and potential inclusion into the database. To date 131 were approved for inclusion and have been captured in the NCCRD and were mapped using captured coordinates spanning a period of 2001-2022. The majority of the adaptation projects that were collected and uploaded in the database are in the water (water security) and agriculture (food security) land use sectors. We further generated another 131 random points on ArcMap 10.4.1. We eventually had 262 points for the analysis of this project.

3.3. LAND USE LAND COVER CHANGE MAPPING FOR THE PERIOD OF 1990-2020

3.3.1 Acquisition of land cover maps

Land use and land cover (LULC) data were derived from the National Land Cover (NLC) Data repository for 1990, 2014, 2018 and 2020 datasets, acquired from Department of forestry, fisheries and the environment (DFFE) (https://egis.environment.gov.za/data_egis/data_download/current, accessed 12 July 2022). The NLC data were derived from remote sensing data, i.e. Landsat (1990, 2014) and Sentinel-2 (2018 and 2020) at 30 and 20 m spatial resolution, respectively. The Landsat images defined in the Universal Transverse Mercator (UTM) 35 South (S) and World Geodetic System 1984 datum (WGS84), while Sentinel images are in the Albers Equal AREA (AEA) projection and World Geodetic system1984 datum (WGS84). The 1990 NLC data was derived from Landsat 5 satellite imagery taken between 1989 and 1991(Musetsho *et al.* 2021; Tizora, 2018). The 2014 NLC data was created from Landsat 8 taken between April 2013 and March 2014 (Ngcofe and Thompson, 2015; Mahlayeye, 2017). The NLC data for 2018 and 2020 were derived from multi-seasonal sentinel 2 imagery acquired between January and December 2018 and 2020, respectively (Thompson, 2019; Thompson, 2020).

The 1990 and 2014 NLC datasets had 72 classes relative to the 2018 and 2020 NLC datasets which had 73 classes. The shapefile for Mpumalanga province was derived from South African provincial boundaries found at the South African Environmental Observation Network (SAEON) (http://www.sasdi.net/metaview.aspx?uuid=a227be54418cf2cf678bc933accff10e, accessed 12 July 2022). The coordinate reference system for the shapefile was Hartebeesthoek94 Datum and Ellipsoid WGS84.

3.3.2 Reprojection, resampling and reclassification of land cover maps

The sentinel images and Mpumalanga study area shapefile were projected into UTM zone 35 S to work with datasets from Landsat. The reprojection was done using projection tool on ArcMap. NLC datasets were confined into the spatial extent of Mpumalanga shapefile using the clipping tool from data management in ArcMap. Landsat and sentinel images were used to detect LULC changes in the study area. Mandanici (2016) shows the benefits and drawbacks of combining sentinel and Landsat images. Alhedyan (2021) also acknowledged that a multi-sensor change detection approach has some image processing limitations, but it still enables the acquisition of a change detection map with a higher level of accuracy. It is requisite for the collection of images to come from similar seasons and have the same spectral and spatial resolution to properly detect LULC changes using multi-sensor images.

Sentinel images were resampled to 30 m spatial resolution for compatibility and comparability with Landsat datasets. Resampling is a mathematical method of interpolating new cell values by converting an existing raster dataset into new coordinates or sizes (Zhu, 2016). Nearest neighbor, bilinear-interpolation, and cubic convolution are popular resampling methods. The nearest neighbor technique converts the value to the nearest pixel, while the pixels are averaged in bilinear interpolation and cubic convolution (Alhedyan, 2021). This study made use of nearest neighbor since it is computationally efficient, retains the input image pixel values for resampling raster cloud and saturation masks, and permits quantification of geometric resampling changes (Ray *et al.* 2016).

To facilitate evaluating and assessing LULC trends, the NLC classes were reclassified into 10 classes. The datasets were reclassified using the South African Land Cover Classification System for remote sensing applications. The reclassify function from spatial analyst was used to reclassify data on ArcMap 10.4.1 (Table 3.2). The legend was harmonized and standardized to ensure comparability (Table 3.3).

Table 3.2: LULC reclassification based on Thompson's standard land cover classification scheme (Thompson, 1996).

Class Number		**Class name**	**Descriptions**
1		Agriculture	Cultivated commercial permanent orchards, cultivated sugarcane pivot irrigated, cultivated sugarcane non-pivot and cultivated emerging farmer sugarcane non-pivot, commercial annual crops pivot irrigated, commercial annual crops pivot irrigated, commercial annual crops pivot irrigated, commercial annual crops non-pivot irrigated, commercial annual crops rain fed/dryland, subsistence/small-scale annual crops, fallow lands & old fields
2		Bareland	Natural rock surface, dry pans, eroded lands, bare riverbed material and other bare
3		Built-up	Residential formal, residential informal, village scattered, village dense, smallholdings, urban recreational fields, commercial, industrial, roads & rails
4		Grasslands	Sparsely wooded grassland and natural grassland
5		Mines and quarries	Surface infrastructure, extraction pits, quarries, tailings and resource dumps and landfills
6		Natural woodlands	Contiguous (indigenous) forest, contiguous low forest & thicket, dense forest & woodland
7		Plantations	Open & sparse plantation forest, open & sparse plantation forest and temporary unplanted (clear-felled) plantation forest
8		Shrubland	Low shrubland (other)
9		Water bodies	Natural rivers, natural pans, artificial dams, artificial sewage ponds, artificial flooded mine pits
10		Wetlands	Herbaceous wetlands

Table 3.3: Harmonized and standardized LULC classes used for change detection analysis.

Land cover types	New classes	NLC 1990 and 2014*	NLC 2018 and 2020*
Natural woodlands	1	4-6	1-4
Plantations	2	32-34	5-7
Shrublands	3	9	8
Grasslands	4	7	12-13
Water bodies	5	1-2	14-21
Wetlands	6	3	22-23
Barelands	7	40-41	25 31
Agriculture	8	10-31	32-46; 73
Built-up areas	9	42-72	47-67
Mines and quarries	10	35-39	68-72

*Land cover class codes according to the South African Land Cover Datasets legend

3.4 ACQUISITION OF THE SOCIOECONOMIC VARIABLES AND ENVIRONMENTAL VARIABLES

A thorough understanding of environmental and socioeconomic vulnerabilities at local scale is critically important for strategic planning and prioritization of climate change adaptation projects or intervention (de Nijs *et al.* 2014). From the environmental point of view, a regional adaptation plan would be considered successful when difficulties brought on by climate change for various operations in the sectors are managed while effective regional adaptation plans also depends on the capacity of stakeholders to engage from a socioeconomic perspective (Vos, 2010). This study used a scenario modelling approach to assess complementarity between adaptation projects with local socioeconomic and environmental factors. Scenario 1: Model based on environmental variables only; Scenario 2: socio-economic variables and final scenario: combining environmental and socio-economic variables.

3.4.1 Environmental variables

The environmental variables used in this study included topographic factors, extreme climate events, changes in LULC and soil properties. The perspectives below describe the role that these environmental variables have in adaption and how they were acquired: The results of global climate change modelling show that the effects of climate change may be extremely severe at high elevations and in areas with complex topography; therefore, topographic information is important for assessing climate change exposure (Dixit, 2011). Lu *et al.* (2020) agreed that there is a need to quantify the topographic influence while preparing for climate change adaptation. This study therefore included topographic parameters such as elevation, aspect, and slope and were obtained from the Digital Elevation Model (DEM) with a spatial resolution of 30 m.The DEM was acquired from United States Geological Survey (USGS, https://earthexplorer.usgs.gov/).

The impacts of global climate change are aggravated by biophysical processes related to land use and land cover at the local and regional levels (Pyke and Andelma, 2007). Hence, it has become important to understand LULC changes in order to assign land use categories while taking the effects of climate change into consideration. Here, we used data on changes in land use and land cover between 1990 and 2020. Soil is increasingly important for modern human societies to meet the global demand for food and fiber, especially in light of the threat of climate change to the agricultural sector. Reid (2010) agrees that one method of adaptation in areas where climate change is projected to reduce seasonal rainfall is to take steps to maximize the amount of soil moisture that is accessible. Priorities in such interventions must be guided by relevant soil properties and landscape considerations. This inspired us to include the soil properties at 250 m spatial resolution from SOILGRIDS (https://soilgrids.org/) in our analysis.

Identifying and characterizing how human and environmental systems are vulnerable to climate is a crucial step in determining where to focus, how to formulate, and how to evaluate adaptation plans (Downing *et al.* 2005). Dynamic downscaled regional model outputs were used to assess climate change over the Mpumalanga province. The dynamic-downscaling simulations are conducted using the conformal-cubic atmospheric model (CCAM), the global Climate model (GCM) that is developed by the Commonwealth Scientific and Industrial Organization (CSIRO) (McGregor, 2005; McGregor and Dix, 2001). In these simulation experiments, CCAM is coupled to the land-surface CSIRO Atmospheric Biosphere Land Exchange model (CABLE), which simulate the land-surface-atmosphere exchange of key fluxes such as water, energy, and greenhouse gases. The CCAM-CABLE boundary forcing includes the bias-corrected seas-surface temperatures (SSTs) and sea-ice fields of six Global Circulation Models (GCMs) that contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5). Here we concentrated into two climate indices or variables such as dry and wet spell. The dry spell is defined as the “maximum length of dry spell: maximum number of consecutive days with rainfall < 1 mm (1961-1990 relative to 2021-2050 period, based on 1.5^0c projections)”. The wet spell is the “maximum length of wet spell: maximum number of consecutive days with RR ≥ 1 mm (1961-1990 relative to 2021-2050 period, based on 1.5^0C projections). The variables were acquired from the CSIR’s Greenbook.

3.4.2 Socio-economic variables

Socioeconomic activities must be considered when developing strategies for climate change adaptation, since they affect people’s capacity and ability to adapt to the changing climate. It is also a crucial ingredient for assessing how different economic sectors and people will be impacted by climate change, with the goal of implementing the necessary adaptation measures. For example: farmers with higher levels of education are more knowledgeable about climate change (Mudombi *et al.* 2014). Education enhances people's ability to make well-informed decisions. Human settlements are significantly impacted by climate change, making them a high priority target for adaptation efforts. The most vulnerable settlements are those that are most exposed to climate change and have the weakest capacity to respond (De Sherbinin, 2007). A study by Sarkodie *et al.* 2022 found that high-income economies have low climate vulnerability, while developing economies have high climate change exposure and sensitivity. The majority of lower income households work in climate-sensitive sectors such as agriculture and fisheries (Zhongming *et al.* 2021). Here, we used key socioeconomic variables from statistics South Africa (Stats SA)'s 2011 database, such as population, settlement type, educational attainment levels (based on adults over the age of 20), and income level categories.

3.4.3 Preparation of environmental and socioeconomic data

Topographic attributes of elevation, slope and aspect were derived from the 30 m Digital Elevation Model in ArcMap 10.4.1. Soil characteristics were acquired pre-processed and stored in a Geographic Tagged Image File Format (GEOTIFF). The masking tool in ArcMap 10.4.1 was used to confine soil properties into the spatial extent of the study area. The spatial join tool in ArcMap 10.4.1 was used to spatially register the socioeconomic data to the shapefile of the study area based on each local municipality. Extreme climate indicators were resampled using bilinear for continuous data and fitted into study area boundary. The data information is shown in Table 3.4.

Table 3.4: Data information table.

Variable category	**Variable Name**	**Data type**
Land use Land cover changes	NLC data 1990 and 2020	continuous
Climate factors	CDD (10,50,90)	continuous
	CWD (10,50,90)	continuous
Topographic factors	Slope	continuous
	Aspect	continuous
	DEM	continuous
Soil Characteristics (Physical soil properties and chemical soil properties)	Bulk density	continuous
	Clay content	continuous
	Coarse fragment	continuous
	sand	continuous
	silt	continuous
	cation exchange capacity (at pH7)	continuous
	nitrogen	continuous
	Soil organic carbon	continuous
	pH	continuous
	Population growth	continuous

Variable category	Variable Name	Data type
Socioeconomic factors	Urban	continuous
	Rural	continuous
	Farm area	continuous
	Income level categories	continuous
	Education level categories	continuous

Cdd = Consecutive Dry Days, Cwd=Consecutive WET Days, DEM = Digital Elevation Model

3.5 DATA ANALYSIS

To develop a framework that integrates the WEF nexus and climate change adaptation to facilitate effective project and programme implementation, we undertook seven general steps: (1) Framework to classify the land use and land cover classes, and climate change adaptation projects into WEF nexus;(3) Comparison of the land LULC Change results and extreme climatic variables with existing or completed climate change adaptation projects;(4) Determine which local municipalities in Mpumalanga has higher hotspot for climate change adaptation projects; (5) Analysis of Land use and Land cover and its impacts on WEF nexus resources over a 30 years period (1990-2020) in Mpumalanga; (6) Modelling the complementarity between existing climate change interventions using environmental and socio-economic data; (7) Highlighting areas where food or water adaptation projects should be prioritized.

3.5.1 LULC change detection

Change detection is the process of examining an object or phenomenon at different times to detect changes in its state (Singh, 1989). It also lays the foundation for a better understanding of the links and interactions between human and natural events, allowing for improved resource management and utilization (Lu, 2004). Following the methodological approach of previous studies (Bekele and Yirsaw, 2019; Chad, 2014; Hassan *et al.* 2016; Munthali *et al.* 2019), the current study employed a post-classification comparison (PCC) method in ArcMap 10.4.1 to detect the location and nature of LULC changes by comparing the extent and areas of LULC classes between two periods (1990 and 2014, 2014 and 2018, 2018 and 2020, 1990 and 2020).This technique shows the direction of change or the transition from one point to another (Musetsho *et al.* 2021). Geometry correction and classification are the most important steps in post classification comparison change detection (Yang and Wen, 2011). The PCC approach used overlay functions in ArcGIS 10.4.1 to create a cross-tabulation matrix (LULC change transition matrix). Quantitative conversions from one LULC category to another were calculated using the LULC change transition matrix on a pixel-by-pixel basis across the examined timeframe. The areas of both gross gains and gross losses were examined in the cross-tabulation matrix for each LULC category. A net change of LULC class was calculated by calculating the difference between the gross gains and gross losses for each LULC category. The method described by

Temesgen *et al.* (2018) was used to calculate the percentage change in LULC between two periods of time:

$$\Delta C = \left(\frac{Af - Ai}{Ai}\right) * 100 \qquad (1)$$

Where Ai denotes the initial year area, *Af* denotes the final year, and *ΔC* is the percentage change in LULC from the first year of coverage. The annual rate of LULC at different periods (1990-2020) was calculated using a formula derived from a compound interest law (Puyravad, 2003):

$$\Delta R = (\frac{1}{t_2} - t1)\ In\ (\frac{A_2}{A_1}) \qquad (2)$$

where ΔR is the annual rate of change for each class per year, A_2 and A_1 are the class areas (ha) at time 2 and time 1 respectively and *t* is time in years interval between the two periods.

3.5.2 Select machine learning model

The 262 points, which were made up of 131 climate adaptation interventions and 131 randomly generated points were all used to extract cell values from multiple rasters at the locations specified in a point feature class and store the values in the attribute table of the point feature class. Due to the categorical nature of the target variable in this study, binomial logistic regression, a type of supervised classification algorithm was employed. Many studies have shown that logistic regression can accurately predict the probability of disease occurrence based on risk factors (Ambrish *et al.* 2022; Nusinovic *et al.* 2020; Saw *et al.* 2020; Zhang and Ma 2021). This shows that the logistic regression model can accurately predict the chances of an event occurring. In the current study, a logistic regression model was used to examine whether the location of climate change adaptation projects or programmes in a lens of WEF nexus could be explained by socio-economic and environmental variables. This probability technique is based on the interaction of climate change adaptations with socioeconomic and environmental variables in a single spatial unit (pixel).

The model based on a generalized linear model (GLM) through logistic regression was implemented using 3 scenarios. Scenario 1: Model based on environmental variables only; Scenario 2: socio-economic variables and final scenario: combining environmental and socio-economic variables. In the dataset provided, a value of 1 denotes the existence of a project or program targeted at adapting to climate change, whereas a value of 0 shows its absence. The independent variables in the logistic regression are listed as x1, x2, x3, etc., and xn. The logistic regression is provided by (3), using the same formular as Lessechen *et al.* (2005), Sperandei (2014) and Kindu *et al.* (2015):

$$Log\ \left(\frac{p}{1-p}\right) = B_{\mathrm{o}} + B_{\mathrm{1x1}}\ +\ B_{\mathrm{2x2}}...B_{\mathrm{nxn}} \qquad (3)$$

The logistic regression uses the log odds of the event in $(\frac{p}{1-p})$, where p is the probability of the occurrence, which in this case indicate the existence of projects or programmes aimed at adapting to climate change. As a result, P is always between 0 and 1. $B0$ is the constant. Bi represent regression coefficients of the reference group and xi denote independent variables.

3.5.3 Implementation

R studio was used to implement the logistic regression model. R studio is an integrated development environment for the r programming language that offers open-source applications for data science, scientific research, and technical communication (https://www.rstudio.com/products/rstudio/download/#download accessed on 08 September 2021). The dataset was randomly divided into two subsets, each of which had 70% and 30% of the total cases. The first subset, which had 70% of the cases, was used for fitting, and the second, which contained 30% of the cases, was used for validation. The model was fitted using the glm () function with the family parameter set to "binomial," which specifies that the response variable has two class categories. A stepwise approach was used to select independent variables that could account for the location of adaptations. The selected variables were latter used in predicting areas that should have climate change adaptation projects and programmes.

3.5.4 Evaluation of logistic regression model

Regardless of being a powerful statistical tool, logistic regression should be employed with caution. To ensure the validity of the findings derived using modern statistical modelling approaches, the model must meet the logistic regression assumptions (Hosmer *et al.* 1991). These assumptions include (1) the independence of errors, which states that all results from the sample group are distinct from one another, (2) there should be a linearity in the logit for any continuous independent variables (e.g. age), meaning there should be a linear relationship between these variables and their respective logit-transformed outcomes, (3) Multicollinearity or redundancy should be avoided, (4) the absence of strongly influencing outliers, which might cause an anticipated outcome of a sample group to be significantly different from their actual outcome arises (Stoltzfuz, 2011).

When the assumptions of logistic regression are not met, issues such as skewed coefficient estimates and excessively high standard errors (Sarkar and Midi, 2010). To avert such issues, it is necessary to assess the relevance of the regression analysis results to the population from which the sample was drawn (Giancristofaro and Salmaso, 2003). Evaluating the performance of the model is essential to avoid getting misleading results that predict outcomes incorrectly. This can be accomplished by evaluating the model fit and its ability to accurately reflect the data. To ensure that the logistic that the logistic regression produces accurate model, the current study used chi-square and residual deviance statistics to assess the fit of the model. These model fit measures examine the difference between actual results and those predicted by the model; poor model fit is indicated by higher test scores denoting a greater discrepancy (Stoltzfus, 2011).

However, summary measures of goodness-of-fit give a single number that summarizes the agreement between the observed and fitted values, which might not give information about specific model components (Ferero and Maydeu, 2009). Hence, a full evaluation of the fitted model requires both the computation of the summary measures and detailed analysis of individual model components (Boateng and Abaye, 2019). The model must then be validated and its discriminating or predicting accuracy should be assessed. The misclassification error rate was then calculated for both training and testing dataset. This is done to figure out the percentage of observations that have been incorrectly classified. The Receiver Operating Characteristic (ROC) and Area Under Curve (AUCs) were used to further evaluate the performance of the model. ROC is used to visualise the discriminatory accuracy of the classifiers/predictors (Park, 2013; Gajowniczek *et al.* 2014) and AUC provides a prediction of the odds of correctly classifying a randomly chosen object; for example, an AUC of 0.8 reflects an 80% chance of classifying the occurrence correctly (Polo and Miot, 2020). In addition, the optimal probability was computed cutoff between conditions that are stable and unstable.

CHAPTER 4: COMPLEMENTARITIES/CO-BENEFITS/SYNERGIES OF WEF NEXUS-BASED ADAPTATION

This chapter will focus on a (1) Framework to classify the land use and land cover classes, and climate change adaptation projects into WEF nexus. (3) Comparison of the land LULC change results and extreme climatic variables with existing or completed climate change adaptation projects. (4) determine which local municipalities in Mpumalanga has higher hotspot for climate change adaptation projects.

4.1 FRAMEWORK TO CLASSIFY THE LAND USE AND LAND COVER CLASSES, AND CLIMATE CHANGE ADAPTATION PROJECTS INTO WEF NEXUS

Based on the criteria outlined in Wolde *et al.* (2021), which highlights the LULC types that are directly linked to the WEF nexus, only 10 classes were chosen for this study from a total of 72 and 73 classes in the LULC data sets (Table 4.1). Previous studies have drawn much public attention to the significant relationship between LULC changes and WEF nexus resources; for example, The effects of land use and land cover changes on rural family food insecurity (Agidew and Singh, 2017), Sustainable energy options and implications for land use (Fritsche *et al.* 2017), Impact of changes in land use and land cover on water availability (Gumindoga *et al.* 2018). Therefore, the study of WEF nexus is inextricably linked to LULC change. However, previous studies focused on independent impacts of LULCC on water, energy, and food. There are currently very few analyses that fully take into consideration the influence of LULC changes on WEF nexus. Table 4.1 indicates the relationships between different LULC categories in the study area and WEF attributes. Understanding relationship beneficial for land use planning since it offers a clear knowledge of trade-offs and synergies across the sectors. Understanding of land use and land cover types in the context of WEF nexus enables collaborative assessment of nexus resources in respect to the environment.

Table 4.1 is showing the results of the relationship between LULC and WEF system.

LULC types	**Water**	**Energy**	**Food**
Plantations	Keep some water for crops, reliable supply of clean, fresh water as well as flood and erosion control and climate regulation	Supply woody biomass, sedimentation protection, and biofuel plants	Earnings to support food access and ecological services connected to food security
Bareland	Water conversation, water loss and evapotranspiration.	Alternative energy and grid infrastructure	Food stress, drought and shock
Agriculture	The need for water, use water for irrigation and responsible for freshwater withdrawals	Utilizes energy for pumping, mechanization and creating biofuels, transportation of food	manufacturing of food

LULC types	Water	Energy	Food
Natural woodlands	critical to the reduction of diffuse pollution, the preservation of river morphology, the regulate stream temperature, and enhance flood risk management while meeting biodiversity requirements	Soil preservation, carbon sequestration and provide fuel wood	Directly supplying food and fuel for food preparation.
Grasslands and Shrubland	Critical in water filtering and purification, water catchments and biodiversity reserves (pollination)	Potentially resource of bioenergy	Grasslands are essential for food production, as they contribute to the production of ruminant milk and meat
Built-up	lower groundwater by (decreasing infiltration), lack of drinking water (as a result of growing consumption) water pollution and flooding	Electricity and natural gas are major sources in commercial buildings	Changing dietary tastes and growing food demand
Water		Essential for electricity generation and groundwater pumping, cultivation of biofuels	Pump-assisted irrigation, transportation, purification,
Mining and quarries	Causes water pollution and water shortages, water is essential for mineral processing	Useful for beneficiation operations and for operation of vehicles and machineries	Decrease agricultural productivity
Wetlands	Improve water quality and increase water security	Ability to influence energy fluxes in favour of latent heat	Improve livelihoods, protect agricultural resources, enhance biodiversity (habitat for fish and wildlife) and reduce impacts from flooding.

The adaptation sectors field from the NCCRD database were classified into respective WEF groups based on the implemented programme and results of adaptation expected from the programme (Table 4.2). This process was done by the project team in coordination with the DFFE and provincial personnel. Figure 4.1 showing the spatial distribution of the WEF organized climate change adaptation projects and programmes within the Mpumalanga province.

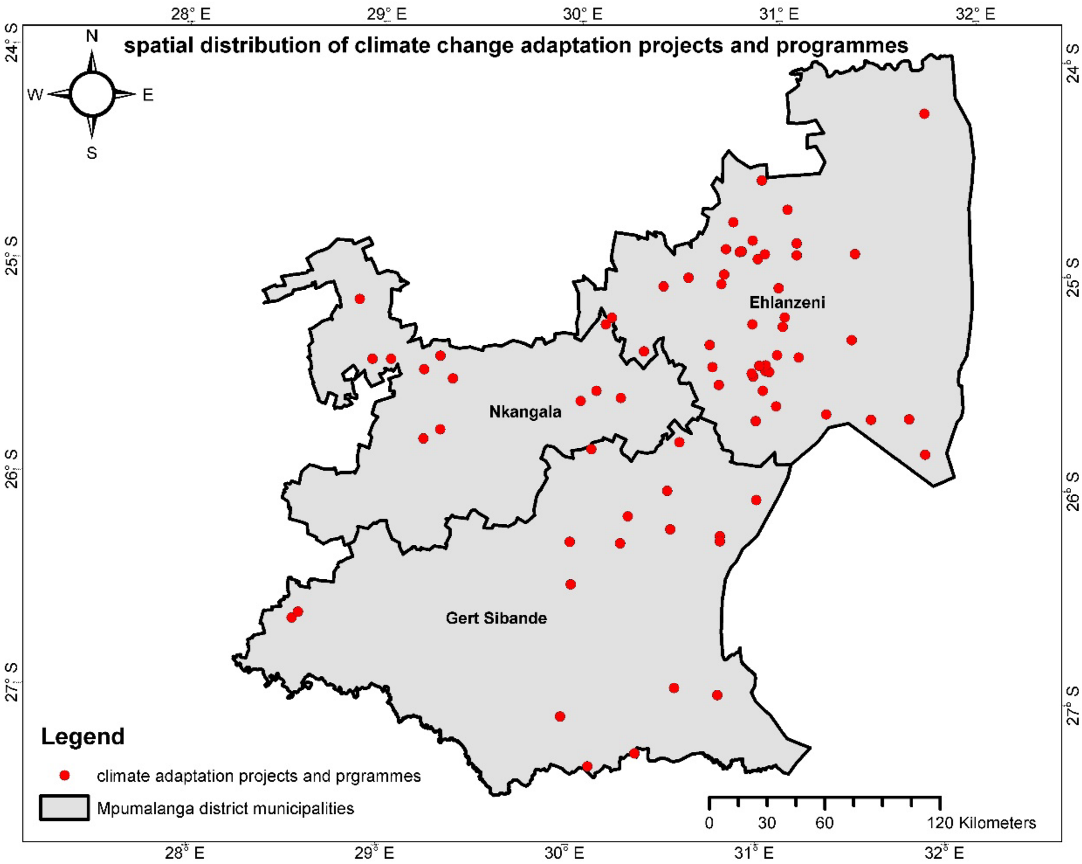


Figure 4.1 spatial distribution of climate change adaptation projects and programmes.

Table 4.2: Natural Resources Management programmes and their contribution to resilience.

Implemented programme	**Expected results from the programme**	**Adaptation sector**
Working for water	The programme increases resilience and reduces vulnerability by addressing problems of water security (quantity and quality, and impediments to its use, including through structural damage, thermal pollution and eutrophication), threats to biological diversity and the ecological functioning of natural systems, the exacerbation of wildfires, flooding, soil erosion, siltation, damage to estuaries and diseases, and problems affecting tourism, transport, trade and recreation.	Water and Biodiversity
Working for land	This needs to look at land as well as fresh water, marine and estuarine habitats. Levels of organic carbon in soils in relation to climate data can provide an indication of the way in which climate is linked to soil	Water and agriculture

Implemented programme	Expected results from the programme	Adaptation sector
	degradation, land use change and farming practices.	
Working for Wetlands	The benefits from rehabilitated wetlands include improved livelihoods, protection of agricultural resources, enhanced biodiversity, cleaner water, reduced impacts from flooding and increased water security.	Water and agriculture
Value added industry	For variety of reasons, the removal of cleared biomass has become critical as it improves water security by improving streamflow and groundwater sources	Water
Working on Fire	Fire frequency and intensity can be correlated to climate and atmospheric CO_2 changes, and in turn provide an indication of the levels of vulnerability applicable to specific plant biomes and urban/rural settlements.	Agriculture (grazing lands)

4.2 COMPARISON OF THE LAND LULCC RESULTS AND EXTREME CLIMATIC VARIABLES WITH EXISTING OR COMPLETED CLIMATE CHANGE ADAPTATION PROJECTS

While our understanding of climate change and its potential impacts has improved, there is still a lack of practical guidance for adaptation (Vogel, 2019). This is due to the uncertainty involved and incompleteness of the knowledge used to plan adaptation, many of the adaptation strategies end up being unsuccessful and wasting financial resources (Schipper, 2020). Adaptation strategies that address local scale climate hazards, stressors, and vulnerabilities are necessary for structuring local impact responses. The impacts of global climate change are exacerbated by biophysical processes connected to land use and land cover at the local and regional levels (Pyke and Andelma, 2007). Hence, an understanding of LULC changes is important for planning and allocating climate change adaptation interventions. Information on current climate conditions is important to guide the planning and implementation of adaptation strategies that address the associated impacts. Thereby, in this section, we will visually compare the adaptation strategies that have been implemented or are still in progress to the corresponding land use activities or climate threats to determine their significance. This is significant since it is important to understand the context in which adaptation projects were developed and how they address the threats and effects that the province's water and agricultural (food security) sectors encounter.

4.2.1 WEF organized Land use and Land cover vs the location of climate change adaptation projects and programmes

It was interesting to notice that the occurrence and expansion of mining and quarries is evident in Nkangala and Gert Sibande municipalities, where agriculture is more dominant and expanding. They have a high implication on the demand and quality of water needed for effective functioning (Ololade *et al.* 2017. There are several more areas where this situation might have serious effects, including threats to ecosystem health, environmental quality (Simpson *et al.* 2019) and risk of civil unrest (Hui and Bao, 2013; Aero et al.2019). Moreover, this resource trilemma is expected to be further complicated by the impacts of climate change. Various adaptation strategies must therefore be integrated into land use planning since related climate change impacts may spatially overlap (Yoon *et al.* 2019). It was even more surprising to notice that the most of land use and land cover changes, particularly in agricultural and coal mining, were centered in Nkangala and Gert Sibande, whereas more adaptation projects were concentrated in the Ehlanzeni district municipality (figure 4.2). This implies that adaptation decisions often involve trade-offs between individual adaptation practices or with other socio-economic or environmental goals.

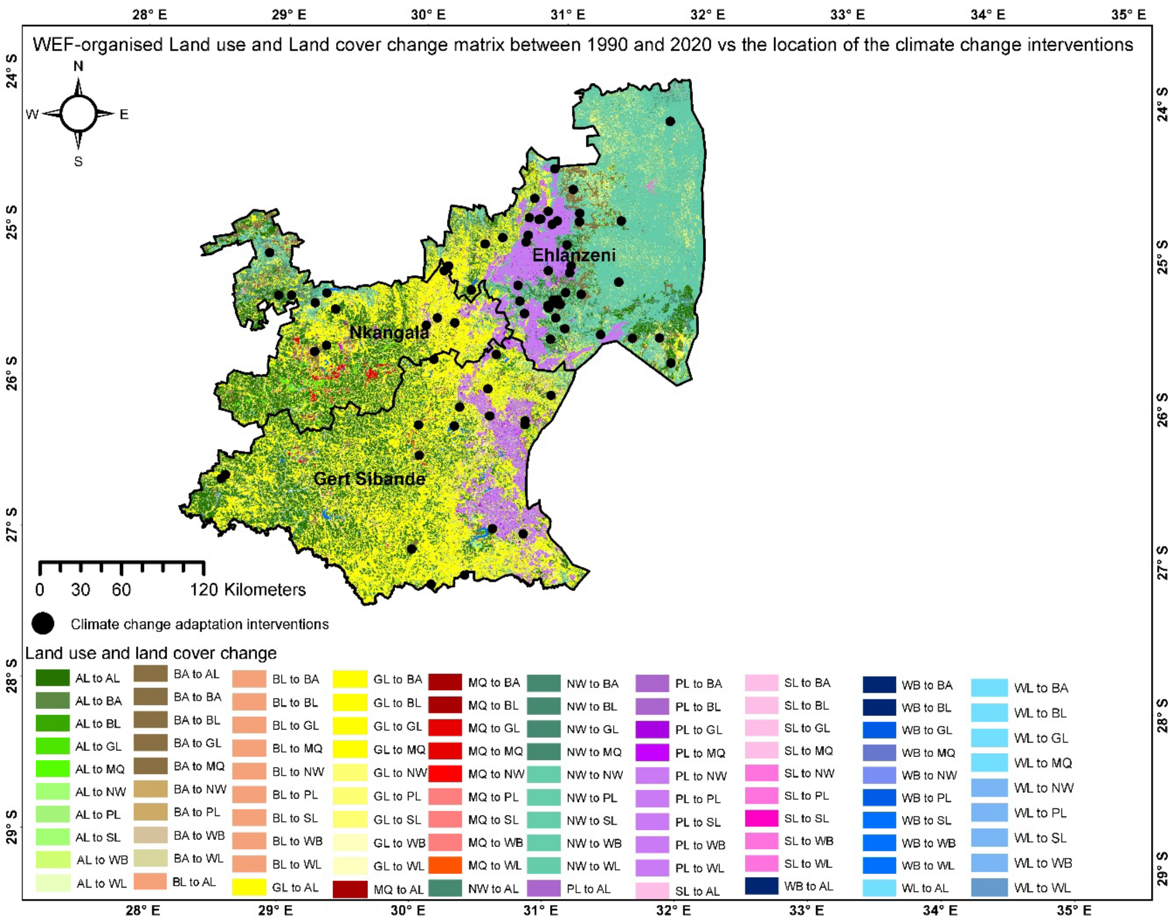


Figure 4.2: Land use and land cover change analysis map, showing the from-to changes of the land use and land cover types of vs spatial distribution of climate change adaptation interventions. *AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands*

4.2.2 Extreme Climatic Variables vs the location of the climate change adaptation projects

The dry spells (2021-2050, based on 1.5^{0}C projections) are evident in the western part of the province, affecting all district municipalities (Figure 4.3). Dry spell could some extent indicate the possible intrusion of drought. Most of the climate change adaptation projects are located in areas of increasing dry spells, which is another positive indicator of complementarity between the underlying environmental change indicators and intervention or adaptation projects (Figure 4.3). The same trends are evident when using the wet spells climate indicator, where the western part of the province is currently experiencing limited or erratic rainfall as compared to the baseline data (1961-1990), with the exception of south of Kruger National Park (Figure 4.4).

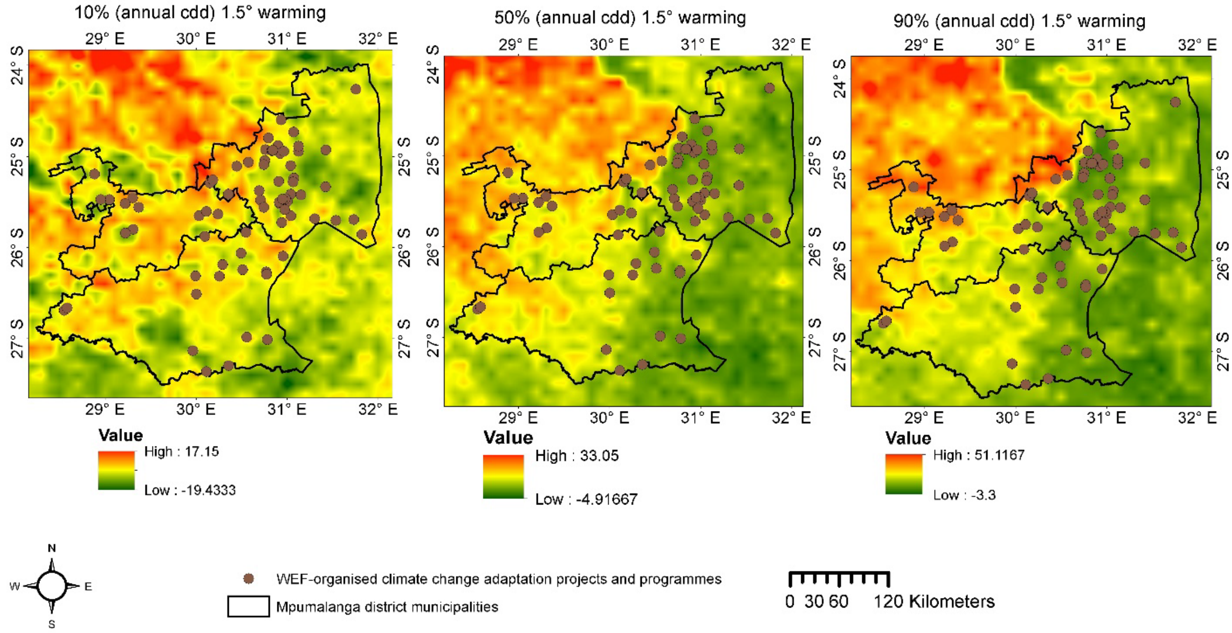


Figure 4.3: Maximum length of dry spell: maximum number of consecutive days with rainfall < 1 mm (1961-1990 relative to 2021-2050 period, based on 1.50C projections).

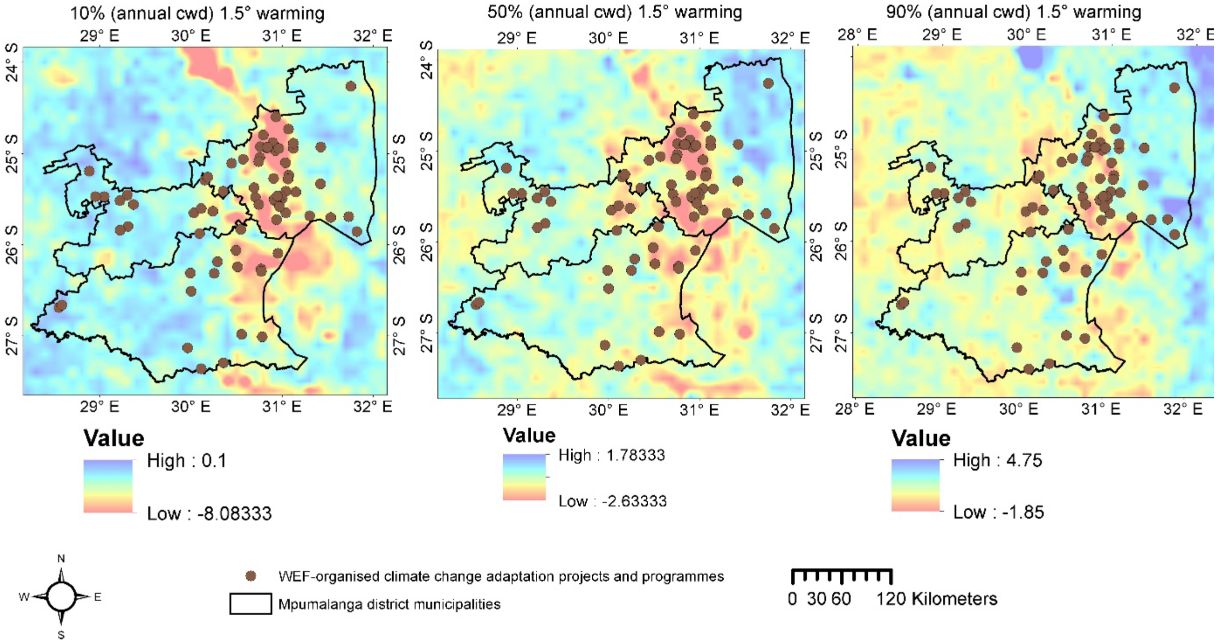


Figure 4.4: Maximum length of wet spell: maximum number of consecutive days with RR ≥ 1 mm (1961-1990 relative to 2021-2050 period, based on 1.5°C projections.

4.3 DETERMINATION OF WHICH DISTRICT MUNICIPALITY IN MPUMALANGA PROVINCE HAS A HIGHER HOTSPOT FOR CLIMATE CHANGE ADAPTATION PROJECTS

The spatial distribution of the provincial climate change adaptation projects and programmes varies from local municipality to local municipality depending on the vulnerabilities as well as other socioeconomic or environmental strategies or goals. There are regions with high concentrations of interventions (hotspots), others with low concentrations (coldspots), and areas in the middle with a moderate concentration of interventions. In Mpumalanga, there are three district municipalities, all of which have had at least some adaptation projects or programmes addressing water or agriculture (food). However, the distribution of adaptation projects or programmes varies spatially (Figure 4.5). High concentrations of adaptation-related interventions have been observed in the Ehlanzeni district municipality, followed by the Nkangala district municipality. While Gert Sibande district municipality is home to a number of economically significant land use activities, such as agriculture, forestry, mining, and grazing land, it can be noticed that the region still has few interventions implemented. This need to be addressed by decision-makers responsible for adaptation.

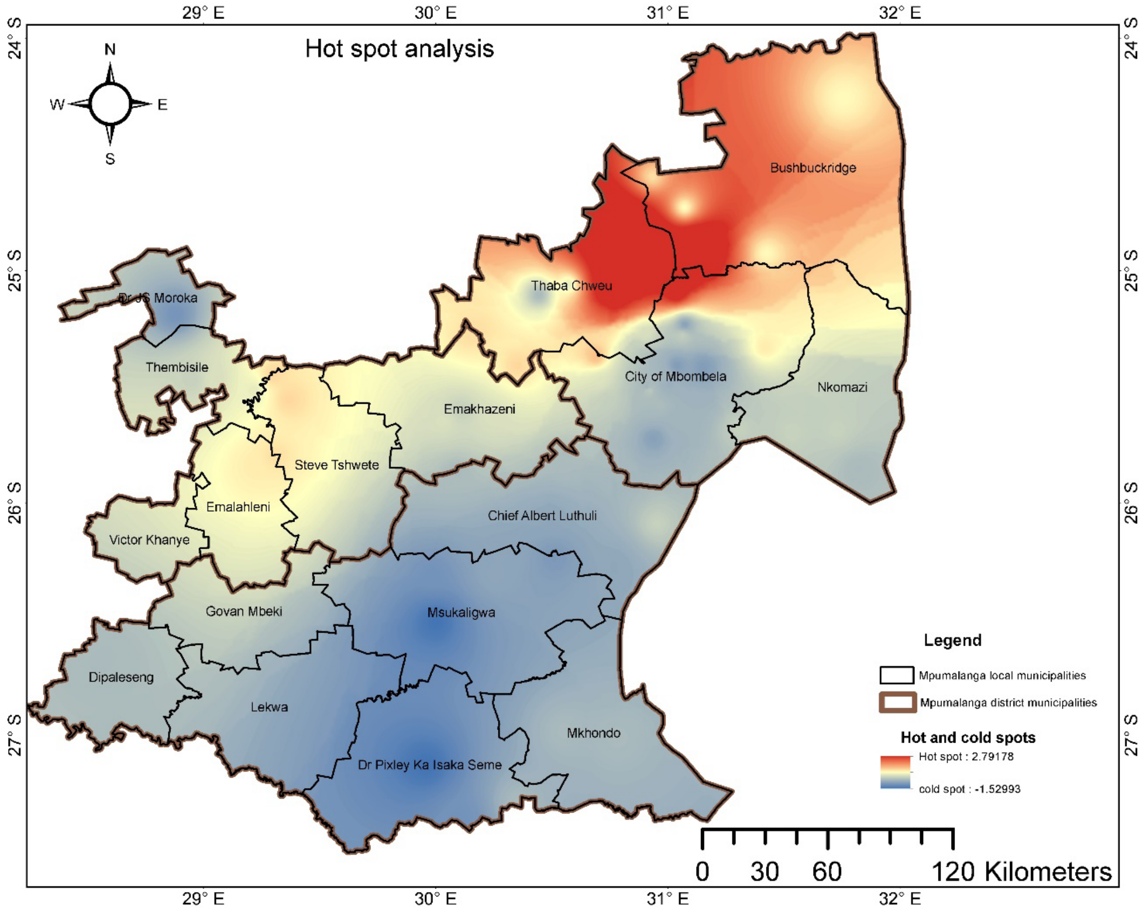


Figure 4.5: Map showing hotspots and coldspots of the Climate change adaptation projects and programmes in Mpumalanga province.

CHAPTER 5: TRADE-OFFS OF THE WEF-NEXUS-BASED ADAPTATION

This chapter will report results on (1) analysis of Land use and Land cover and its impacts on WEF nexus resources over a 30-year period (1990-2020) in Mpumalanga; (2) Modelling the complementarity between existing climate change interventions using environmental and socio-economic data; (3) highlighting areas where food or water adaptation projects should be prioritized.

5.1.1 Accuracy assessment for the land use and land cover change

No accuracy assessment was conducted on the 1990 National Land-Cover dataset due to lack of suitable reference data. However, since 1990 NLC data was generated using the same mapping and modelling processes and image formats as the 2013/14 dataset the map accuracies determined for the 2013-14 dataset can be used as a reliable indication of the likely mapping accuracies achieved for the 1990 dataset (image, 2016). The 2014 NLC dataset had an overall map accuracy of 83.73%, with a mean LULC class accuracy of 91.27% (Image, 2015). This was calculated using 6415 sample (30 representing 33 different LULC classes) and a kappa index of 80.31%, implying that the results are exceedingly unlikely to be the result of random chance (Image, 2015). The 2018 NLC dataset has an overall map accuracy of 91.32% derived from 6570 reference points (Thompson, 2019) while the 2020 NLC has an overall accuracy of 85.47% based on 6835 reference points (Thompson, 2020).

5.1.2 Multicollinearity diagnostic results of predictor variables

VIF was employed in the analysis of this study to diagnose the multicollinearity among the spatial predictor variables. The results are shown in Figure 5.1, Figure 5.2, and Figure 5.3. In each scenario, the minimum tolerance for the explanatory variables was greater than the critical value of 0.1. In scenario 1, which is based only on environmental variables, the three variables were found to be strongly correlated with one another. They were therefore removed to prevent multicollinearity. The highest variance inflation factor was 4.13, which is below the threshold of 5 (see Figure 5.1). The VIF values in scenario 2 were ranging from 1.17 to 2.05 (with a corresponding tolerance level of larger than 0.1). The multicollinearity of this model was so severe that only 4 variables were considered for analysis from the total of 49 variables (see Figure 5.1). The education level categories were strongly corelated with employment status and settlement type. Due to multicollinearity, only 18 of the 69 total predictor variables were used in scenario 3 (see Figure 5.3).

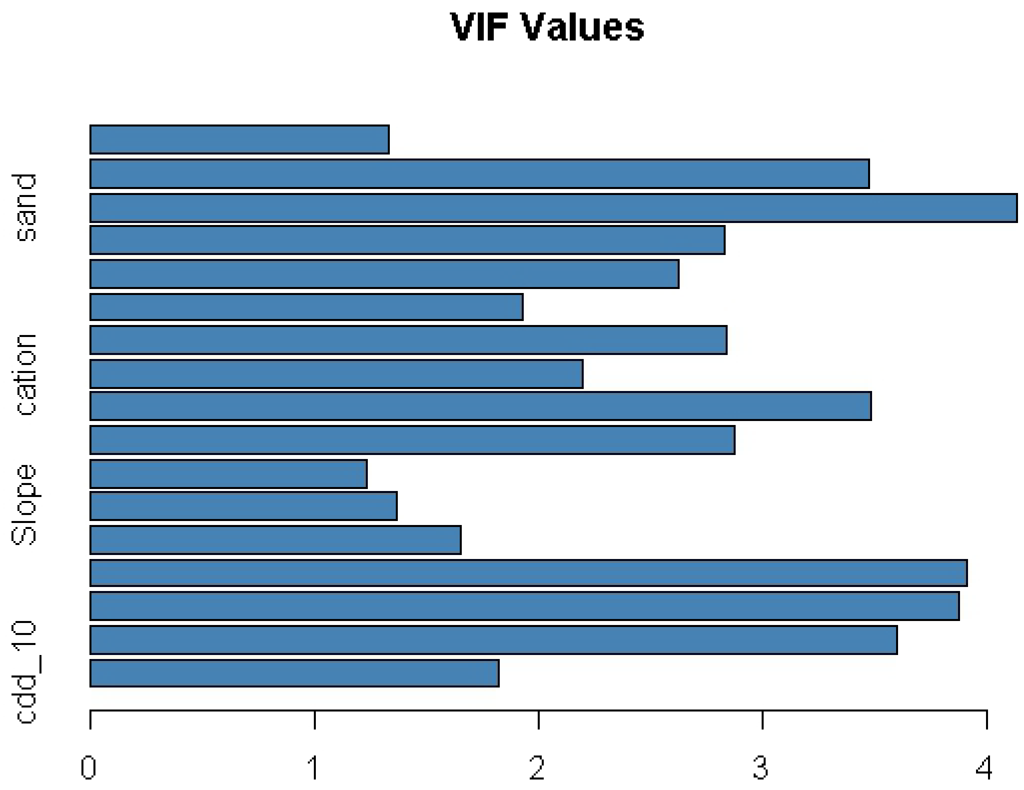


Figure 5.1: multicollinearity diagnosis of predictor variables based on Scenario 1.

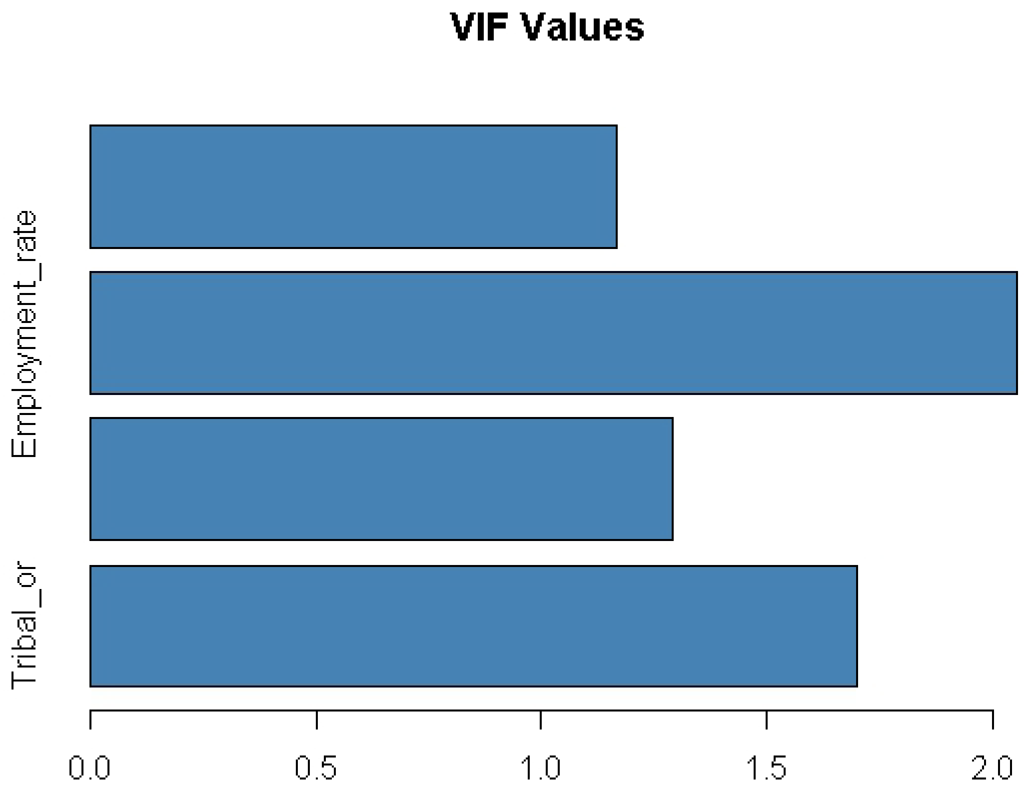


Figure 5.2 multicollinearity diagnosis of predictor variables based on Scenario 2.

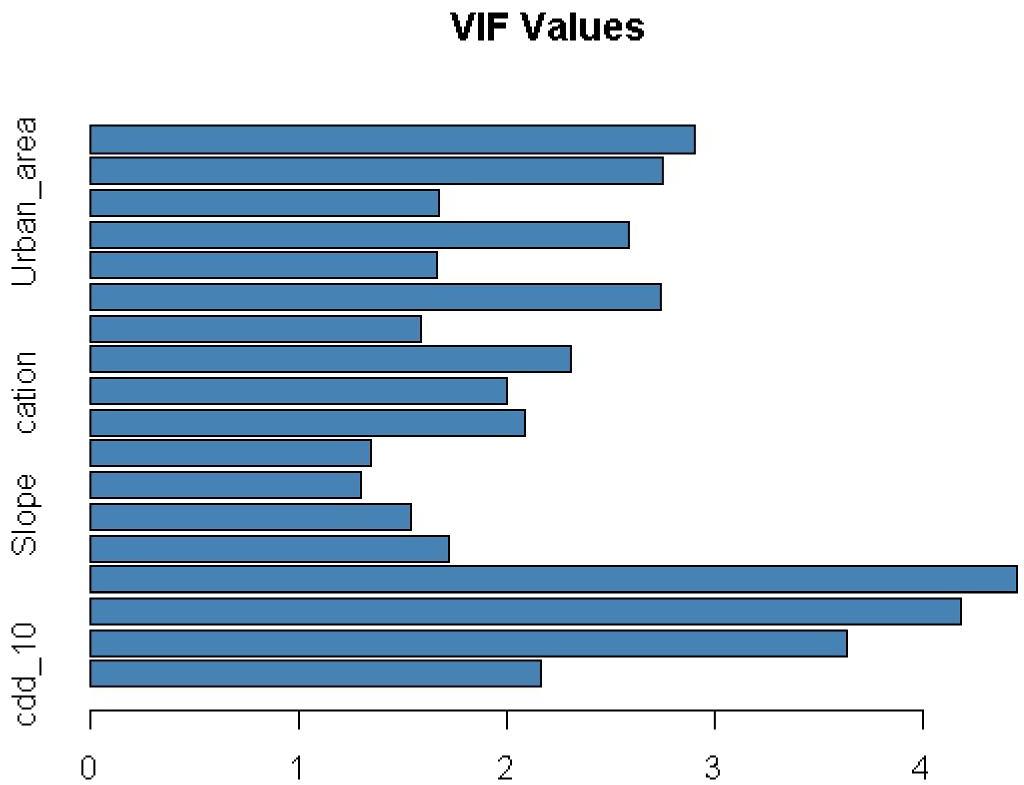


Figure 5.3 multicollinearity diagnosis of predictor variables based on Scenario 3.

5.2 ANALYSIS OF LAND USE AND LAND COVER AND ITS IMPACTS ON WEF NEXUS RESOURCES OVER A 30-YEAR PERIOD (1990-2020) IN MPUMALANGA

Figure 5.4 shows LULC maps for 10 LULC classes that are being investigated. During the entire study period (1990-2020), agriculture, grasslands, natural woodlands and plantations were predominant LULC classes (see Figure 5.4 and figure 5.5). In 1990, agriculture, barelands, built-up areas, grasslands, mines and quarries, natural woodlands, plantations, shrublands, water bodies and wetlands covered 18.82%, 0.15%, 2.33%, 37.36%, 0.61%, 26.29%, 9.70%, 1.09%, 0.53% 3.10% (Table 5.1). The LULC areas under agriculture, grasslands, shrublands and wetlands decreased from 18.84% (1443997.4 ha), 37.36% (2863977.66 ha), 1.09% (83336.31 ha) and 3.10% (237623.85 ha) in 1990 to 17.06% (1308009.69 ha), 36.63% (2808024.57 ha), 0.54% (41641.38 ha) and 2.66% (204214.77ha) in year 2014. On other hand barelands, built-up areas, mines and quarries, natural woodlands, plantations and water increased from 0.15% (11430.18 ha), 2.33% (178984.26 ha), 0.61% (46508.13 ha), 9.70% (743359.05 ha) and 0.53% (40911.21 ha) in year 1990 to 0.32% (24615.27 ha), 2.80% (214485.84 ha), 1.01% (77710.5 ha), 9.81% (752154.66 ha) and 0.59% (45608.49 ha) in year 2014. This might be attributed to the increased global demand for energy. South Africa generated about 253 TWh of power in 2014, 92% of which was generated by coal (Energiewende, 2017). Most South Africa's coal mines and power plants are located in the province of Mpumalanga (Prinsloo *et al.* 2021).

The increase of natural woodlands and forest plantations indicates the importance of resources to the provincial economy. This province is renowned for its unique indigenous forests and for being the main location for forestry production in South Africa. The province has a considerable quantity of rainfall (Simpson *et al.* 2019), thus it was not surprising to see an increase in the quantity of water bodies. Agriculture which was 17.06% (1308009.69 ha) in 2014, has shown a dramatically increment and constantly maintain the second position in terms of area percentage in 2018 (23.48%). With barelands, built-up areas, plantations, and water bodies the trend continued the same up to 2018 except for mines and quarries, and natural woodlands. However, wetlands have experienced a slightly increase from 2.66% (204214.77 ha) in 2014 to 3.42% (262225.26 ha) in 2018. During the study period 2018 to 2020, the LULC with increased area were agriculture, built-up areas, natural woodlands from 23.38% (1792095.48 ha), 3.40% (260757.45 ha), 25.30% (1939256.82 ha) in 2018 to 23.73% (1818913.23 ha), 3.41% (261126.81 ha) and 26.92% (2063747.52 ha). Between 2018 and 2020, there was an slight decrease in the water bodies and wetland areas. This may be linked to the drought episodes that have affected the Mpumalanga province between 2015 and 2017 (Ebhuoma *et al.* 2020).

The results of the analysis over the study period (1990-2020) shows that the LULC areas under agriculture, built-up areas and mines and quarries increased from 18.84% (1443997.44ha), 2.33% (178984.26ha) and 0.61% in 1990 to 23.73% (1818913.23ha), 3.41% (261126.81ha) and 0.79% (60506.1ha) in 2020. While grasslands have decreased from 37.36% (2863977.66ha) in 1990 to 30.39% (2329362.18ha) in 2020. These major land use activities appear to be expanding at the expense of grasslands. The shrinking in grass cover incapacitates the ability of the ecosystem to control and reverse the effects of climate change by altering the earth’s surface albedo, radiative balance and global carbon cycle (Jia *et al.* 2022).

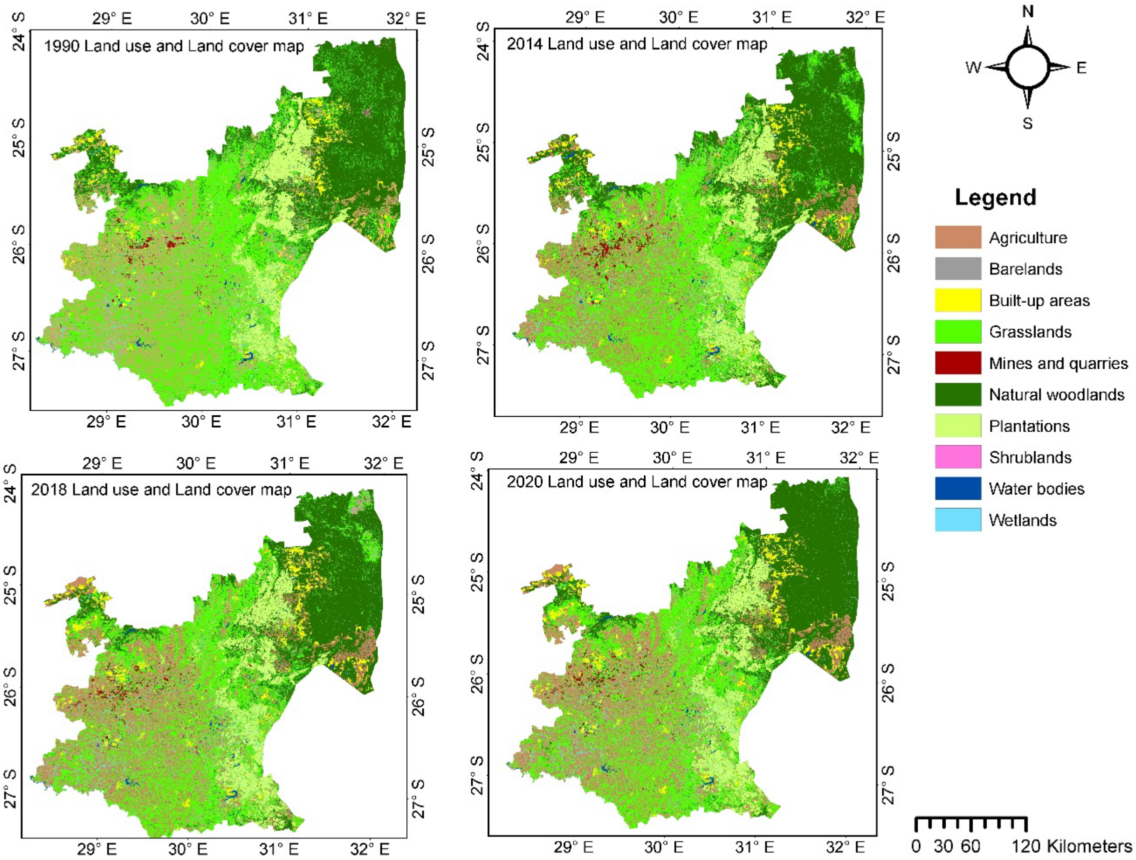


Figure 5.4: LULC maps for 1990, 2014, 2018 and 2020.

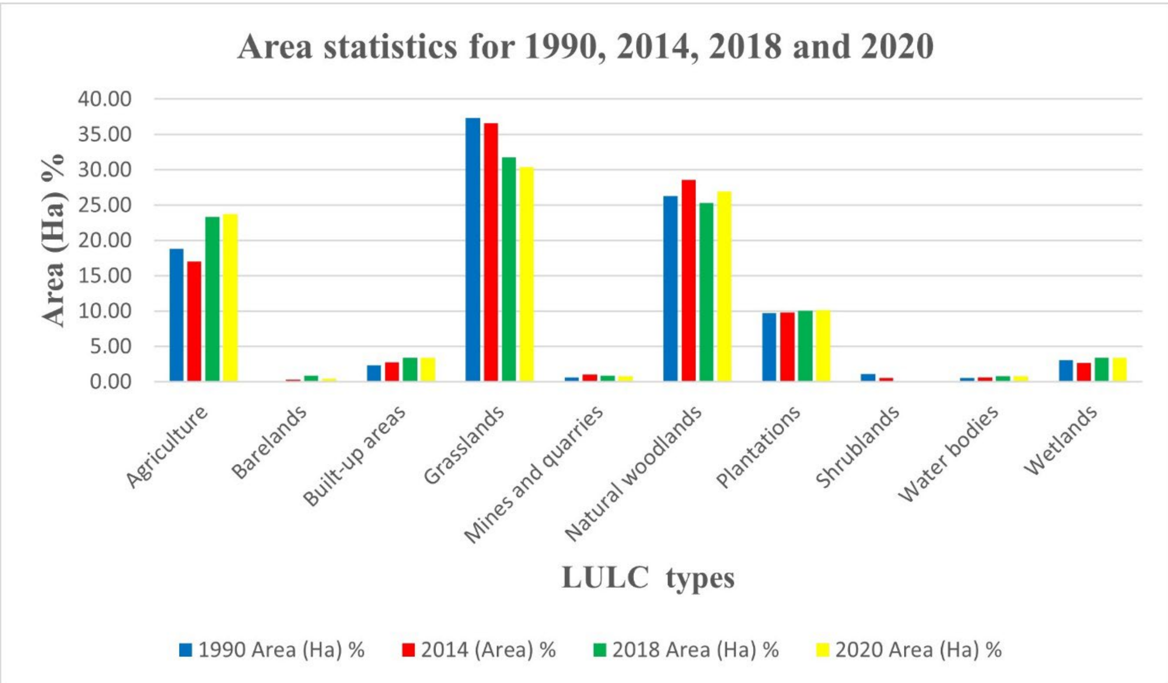


Figure 5.5: Area statistics of land use and land cover maps for various years.

Table 5.1: Mpumalanga LULC area.

LULC Types	1990 Area (ha)	1990 Area (Ha) %	2014 Area (ha)	2014 (Area) %	2018 Area (ha)	2018 Area (Ha) %	2020 Area (Ha)	2020 Area (ha) %
Agriculture	1443997.44	18.84	1308009.69	17.06	1792095.48	23.38	1818913.23	23.73
Barelands	11430.18	0.15	24615.27	0.32	67543.83	0.88	35719.65	0.47
Built-up areas	178984.26	2.33	214485.84	2.80	260757.45	3.40	261126.81	3.41
Grasslands	2863977.66	37.36	2808024.57	36.63	2440055.88	31.83	2329362.18	30.39
Mines and quarries	46508.13	0.61	77710.5	1.01	64710.63	0.84	60506.1	0.79
Natural woodlands	2015718.39	26.29	2189381.31	28.56	1939256.82	25.30	2063747.52	26.92
Plantations	743359.05	9.70	752154.66	9.81	769851	10.04	776071.98	10.12
Shrublands	83336.31	1.09	41641.38	0.54	10199.43	0.13	44.55	0.00
Water bodies	40911.21	0.53	45608.49	0.59	59150.7	0.77	58541.85	0.76
Wetlands	237623.85	3.10	204214.77	2.66	262225.26	3.42	261812.61	3.42
Total	**7665846.48**	**100.00**	**7665846.48**	**100.00**	**7665846.48**	**100.00**	**7665846.48**	**100.00**

5.2.1 LULC area percentage, net change, percentage increase/decrease annual rate of change

LULC classes in the study area have witnessed large net gains and losses over the study period (Figure 5.6). For example, during the initial phase of the research phase (1990-2014), barelands, mines and quarries and built-up areas have increased by 115.35%, 67.09% and 19.84% at an annual rate of change of 3.19% ha^{-1}, 2.14% ha^{-1} and 0.75% ha^{-1}% respectively. On the contrary, shrublands, wetlands and agriculture have declined by 50.03%, 14.06% and 9.42% at -2.89% ha^{-1}, -0.63% ha^{-1} and -0.41% ha^{-1}, respectively (Table 5.2). Extensive changes in land use changes can lead to soil erosion, decline in agricultural production, and land degradation (Kuma *et al.* 2022), particularly in areas with steep slopes like Mpumalanga. Due to the ongoing competition for land use between agricultural and mining operations, inadequate soil and water management practices, deforestation, the removal of natural vegetation, and the use of heavy machinery are likely to be blamed for the significant increase in barelands areas between 1990 and 2014.

During the second phase of the study (2014-2018) the yearly rate of change demonstrated a different shifting trend for most LULC classes (Table 5.3). For agriculture and wetlands the long-term annual rate of change has significantly risen from -0.41% ha^{-1} to 7.9% ha^{-1}, -0.63% ha^{-1} to 6.3% ha^{-1}, respectively, whereas annual rate of change has significantly declined for mines and quarries and natural woodlands from 2.14% ha^{-1} to -4.6% ha^{-1} and 0.34% ha^{-1} to -3% ha^{-1}.The LULC change trend for barelands and built-up areas continues the same as their annual rate of change continued to increase from 3.19% ha^{-1} to 25.2% ha^{-1} and 0.75% ha^{-1} to 4.9% ha^{-1}. Mining areas are popular destinations for migrants due to their employment opportunities, availability of infrastructure and services, resulting in a sharp increase in population (Siyongwana and Shabalala, 2019; Ntema *et al.* 2017). Therefore, the need for infrastructure such as roads and buildings because of the growing population has led to an expansion in built-up areas. During the same period, barelands and built-up areas occupied top positions in term of percentage increase.

However, during the final phase of the study period (2018-2020), there was a different shifting trend for barelands. barelands have experienced a dramatically declined of about -47.12% at an annual rate of change -31.85% ha^{-1}, from land area 67543.83 ha to35719.65 ha (Table 5.4). The water bodies and wetlands have also experienced a drastically loss by -1.03% at an annual rate of change of -o.51% ha^{-1} and -0.16% at an annual rate of change -0.08% ha^{-1} respectively. Throughout the duration of the study (1990-2020), shrublands declined by 99.95% at annual rate of change of 25.11% ha^{-1} which was the largest loss in the duration of research, and it is followed by grasslands class which declined by18.67% at an annual rate of change 0.69% ha^{-1} (Table 5.5). The shrublands class is the most LULC class that experienced drastically loss throughout the study. Afforestation can also be blamed for the decrease in grasslands and shrublands because of the severe harm it does to Mpumalanga's biodiversity, as described by Allan *et al.* (1997). Allan *et al.* (1997) reported that a large portion of intended new afforestation is targeted in areas with a wide variety of grassland bird species, vulnerable grassland bird species. Barelands, built-up areas, agriculture and mines and quarries are the most LULC classes that experienced significant gains in the study area.

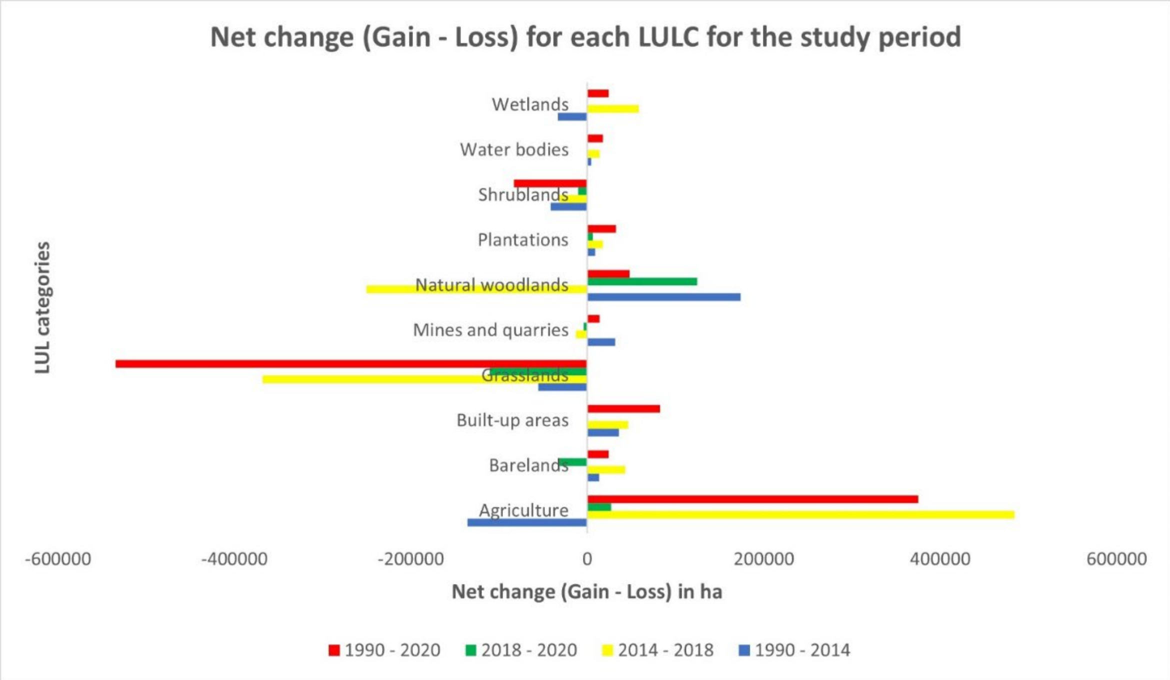


Figure 5.6: Net change for each LULC category for the study period.

Table 5.2: LULC area percentage, net change percentage, percentage increase/decrease and annual rate of change (1990-2014).

LULC Names	1990 Area (Ha) %	2014 Area (ha) %	Change in LULC % coverage	Percentage increase/decrease	Annual rate of change %
Agriculture	18.84	17.06	-1.77	-9.42	-0.41
Barelands	0.15	0.32	0.17	115.35	3.19
Built-up areas	2.33	2.80	0.46	19.84	0.75
Grasslands	37.36	36.63	-0.73	-1.95	-0.08
Mines and quarries	0.61	1.01	0.41	67.09	2.14
Natural woodlands	26.29	28.56	2.27	8.62	0.34
Plantations	9.70	9.81	0.11	1.18	0.05
Shrublands	1.09	0.54	-0.54	-50.03	-2.89
Water bodies	0.53	0.59	0.06	11.48	0.45
Wetlands	3.10	2.66	-0.44	-14.06	-0.63

Table 5.3: LULC area percentage, net change percentage, percentage increase/decrease and annual rate of change (2014-2018).

LULC Names	2014 Area (%)	2018 Area (%)	Change in LULC % coverage	Percent increase/decrease	Annual rate of change %
Agriculture	17.06	23.38	6.31	37.01	7.9
Barelands	0.32	0.88	0.56	174.40	25.2
Built-up areas	2.80	3.40	0.60	21.57	4.9
Grasslands	36.63	31.83	-4.80	-13.10	-3.5
Mines and quarries	1.01	0.84	-0.17	-16.73	-4.6
Natural woodlands	28.56	25.30	-3.26	-11.42	-3
Plantations	9.81	10.04	0.23	2.35	0.6
Shrublands	0.54	0.13	-0.41	-75.51	-35.2
Water bodies	0.59	0.77	0.18	29.69	6.6
Wetlands	2.66	3.42	0.76	28.41	6.3

Table 5.4: LULC area percentage, net change percentage, percentage increase/decrease and annual rate of change (2018-2020).

LULC Names	2018 Area (%)	2020 Area (%)	Change in LULC % coverage	Percent increase/decrease	Annual rate of change %
Agriculture	23.38	23.73	0.35	1.50	0.74
Barelands	0.88	0.47	-0.42	-47.12	-31.85
Built-up areas	3.40	3.41	0.00	0.14	0.07
Grasslands	31.83	30.39	-1.44	-4.54	-2.32
Mines and quarries	0.84	0.79	-0.05	-6.50	-3.36
Natural woodlands	25.30	26.92	1.62	6.42	3.11
Plantations	10.04	10.12	0.08	0.81	0.4
Shrublands	0.13	0.00	-0.13	-99.56	-271.67
Water bodies	0.77	0.76	-0.01	-1.03	-0.51
Wetlands	3.42	3.42	-0.01	-0.16	-0.08

Table 5.5: LULC area percentage, net change percentage, percentage increase/decrease and annual rate of change (1990-2020).

LULC Names	1990 Area (%)	2020 Area (%)	Change in LULC % coverage	Percentage increase/decrease	Annual rate of change %
Agriculture	18.84	23.73	4.89	25.96	0.77
Barelands	0.15	0.47	0.32	212.50	3.79
Built-up areas	2.33	3.41	1.07	45.89	1.26
Grasslands	37.36	30.39	-6.97	-18.67	-0.69
Mines and quarries	0.61	0.79	0.18	30.10	0.877
Natural woodlands	26.29	26.92	0.63	2.38	0.08
Plantations	9.70	10.12	0.43	4.40	0.14

LULC Names	1990 Area (%)	2020 Area (%)	Change in LULC % coverage	Percentage increase/decrease	Annual rate of change %
Shrublands	1.09	0.00	-1.09	-99.95	-25.11
Water bodies	0.53	0.76	0.23	43.09	1.19
Wetlands	3.10	3.42	0.32	10.18	0.32

5.2.2 LULC change (Transition) matrix

The LULC change matrix (Table 5.6, Table 5.7, Table 5.8, and Table 5.9) shows the distribution of major transitions in the 10 LULC categories from 1990-2014, 2014-2018, 2018-2020 and 1990-2020. Moreover, the results of LULC change matrix reveal significant LULC changes in Mpumalanga. Table 5.6 shows that between 1990 and 2014, the conversion area of agriculture was (310566.04 ha) 25.1%, with 13.62% converted being to grasslands, 0.08% into water bodies and 1.77% into mines and quarries. During the same period 53.46% of mines and quarries remain unchanged, while the remaining area of mines and quarries was converted to agriculture (1.36%), natural woodlands (6.71%), plantations (0.73%), grasslands (35.04%), shrublands (0.12%) and water bodies (0.06%), respectively. The conversion area of natural woodlands was 19.59% (394981.12 ha), with 2.13% converted to agriculture, 14.22% into grasslands, 0.39% into water bodies, 0.07% into mines and quarries. Of the 118800.36 ha (15.98%) converted plantation areas, 7.33% and 0.67 were converted for grasslands and agriculture, respectively. Water bodies experienced the transaction of about 23.18% (9485.1 ha) area whereas 31426.11 ha remained unchanged.

Between 2014 and 2018, about 1160657.1 ha (88.73%) of agriculture persisted, while the remaining agricultural area of (147352.59 ha) 11.26% changed to grasslands (7.15%), mines and quarries (0.45%), natural woodlands (2.39%), plantations (0.29%), water bodies (0.03%) and wetlands (0.31%) (Table 5.7). In the same period 83.88%, 8.12%, 34.11%, 28.72%, 14.45% and 32.93% of total areas of barelands, built-up areas, grasslands, natural woodlands, plantations and wetlands were changed to different classes. On other hand 51.79% (40253.22 ha) of mines and quarries remained unchanged, while 37457.28 were changed to other classes, the majority being converted to grasslands (37.32%), water bodies (3.85%) and agriculture (2.52%). About 83.65% of water bodies remained persisted while 7456.59 ha (16.35%) was changed to other classes.

Table 5.8 and figure 5.9 shows the transition matrix between 2018 and 2020. A total area of 568655.37 ha (7.41%) has changed. Agriculture, mines and quarries, natural woodlands, shrublands, plantations and water bodies are among the classes that changed to other LULC classes accounting for 1.53%, 24.19%, 6.95%, 99.93%, 2.77% and 12.92%, respectively. During this period shrublands experienced highest transition, most of shrublands converted to natural woodlands (88.23%) and grasslands (11.19%). Majority of natural woodlands, plantations and water bodies classes were changed to grasslands and agriculture. The transition matrix based on post-classification comparisons shows that 90.23%, 12.75%, 88.05%, 64.91%, 27.08%, 79.02%, 80.95, 0.01%, 80.65% and 53.31% of the total areas of agriculture, barelands, built-up areas, grasslands, mines and quarries, natural woodlands, plantations, shrublands, water bodies and wetlands remained unchanged.

Table 5.9 demonstrates that shrublands and barelands experienced the most conversions, with 99.99% and 87.12% of their LULC areas changed into other classes, respectively, throughout the study's 30-year timeframe. Based on the transition matrix (table 5.9 and figure 5.10), about 55.56% of total mines and quarries in 1990 was changed into grasslands in 2020 while about 12.42% of grasslands in 1990 was converted into agriculture in 2020. During the same period, the conversion area of agriculture was 140958.9 ha (9.76%), with 3.83% converted into grasslands, 1.62% into mines and quarries, 2.43% into plantations and 0.16% into water bodies. It is evident from the LULC change (transition) matrix results that the competition between coal mining and agriculture for land and water use is the impetus for rapidly LULC changes. De Laurentiis *et al.* (2016) found that food and energy are closely linked due to the reliance on fossil fuels and bio-fuel expansion. This has made energy and food production competitors for land and water. Both opponents have a negative impact on the environment, particularly on soil composition, water quality, and the loss of natural habitats (Haddaway *et al.* 2019; Rohila *et al.* 2017).

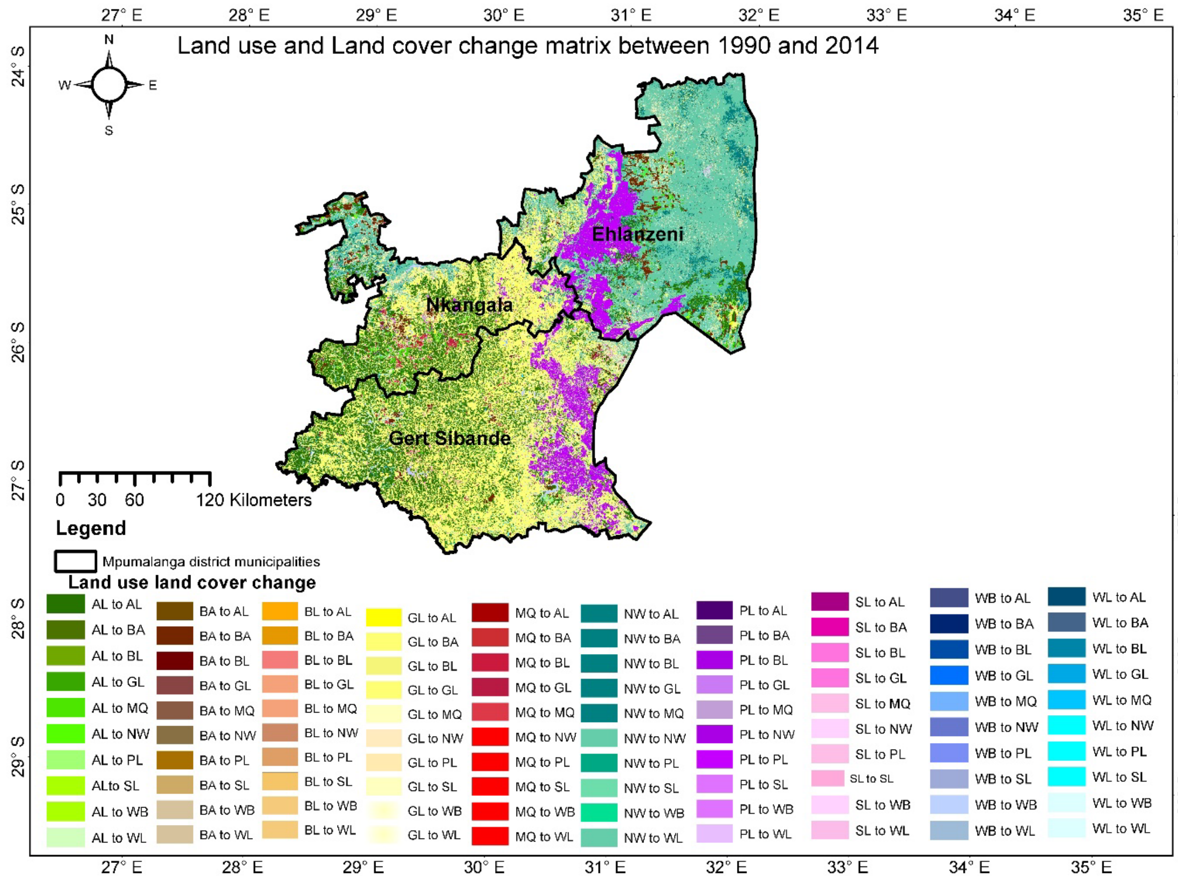


Figure 5.7: Land use and Land cover change matrix map between 1990 and 2014. AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands

Table 5.6: LULC change matrix between 1990 and 2014.

		Land class 2014										
	LULC Names	**Agriculture**	**Barelands**	**Built-up areas**	**Grasslands**	**Mines and quarries**	**Natural woodlands**	**Plantations**	**Shrublands**	**Water bodies**	**Wetlands**	**Total**
Land class 1990	Agriculture	**1133431.4**	1885.68	4624.11	196697.25	25638.75	58472.64	10393.29	2412	1128.24	9314.1	**1443997.44**
	Barelands	243.72	**2861.91**	298.98	4009.59	25.02	2060.55	92.25	369.45	1156.86	311.85	**11430.18**
	Built-up areas	2368.98	194.04	**161115.84**	5452.92	423.09	7507.44	862.74	420.03	20.97	618.21	**178984.26**
	Grasslands	110013.93	10783.44	24077.07	**2140367.49**	21329.73	415124.64	92593.44	21343.41	4943.97	23400.54	**2863977.66**
	Mines and quarries	632.97	118.35	277.02	16298.19	**24865.29**	3122.28	341.64	54.18	28.89	769.32	**46508.13**
	Natural woodlands	43021.26	3263.76	18242.55	286655.76	1509.21	**1620737.19**	18769.41	10884.96	4792.86	7841.43	**2015718.39**
	Plantations	5039.82	499.68	2602.98	54503.01	2660.31	44955.36	**624558.69**	897.21	617.31	7024.68	**743359.05**
	Shrublands	6110.28	3157.02	2666.43	50046.3	265.32	13827.78	1861.83	**4757.31**	342.36	301.68	**83336.31**
	Water bodies	74.97	1343.07	130.23	2487.6	27.9	2165.85	202.59	123.75	**31426.11**	2929.14	**40911.21**
	Wetlands	7072.38	508.32	450.63	51506.46	965.88	21407.58	2478.78	379.08	1150.92	**151703.8**	**237623.85**
	Total	**1308009.7**	**24615.27**	**214485.84**	**2808024.57**	**77710.5**	**2189381.31**	**752154.66**	**41641.38**	**45608.49**	**204214.8**	**7665846.48**

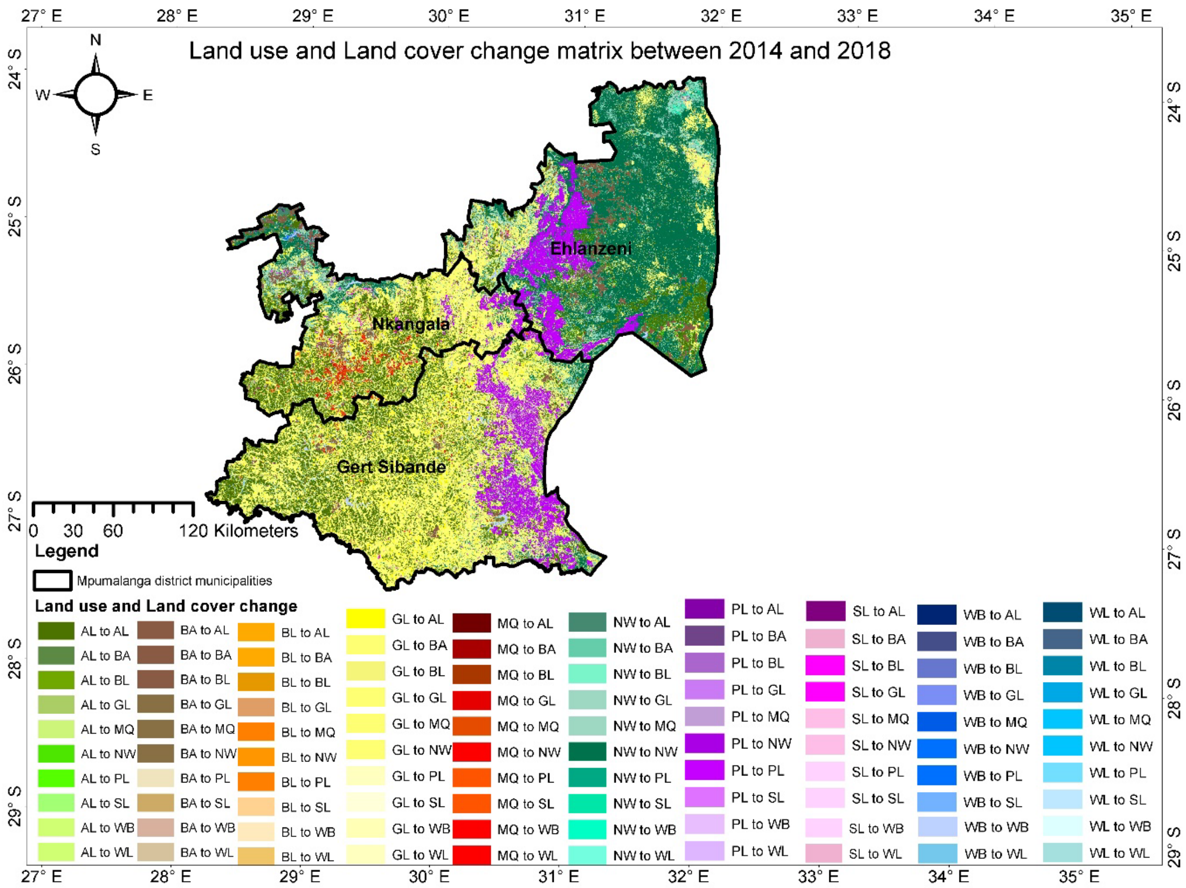


Figure 5.8: Land use and Land cover change matrix map between 2014 and 2018. *AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands*

Table 5.7: LULC change matrix between 2014 and 2018.

		Land class 2018										Total
	LULC names	**Agriculture**	**Barelands**	**Built-up areas**	**Grasslands**	**Mines and quarries**	**Natural woodlands**	**Plantations**	**Shrublands**	**Water bodies**	**Wetlands**	
Land class 2014	**Agriculture**	**1160657.1**	2246.22	5983.38	93496.23	5957.01	31330.98	3908.97	4.23	329.04	4096.53	**1308009.69**
	Barelands	2119.23	**3965.85**	1344.06	9587.61	1915.11	2469.78	514.98	6.93	2222.01	469.71	**24615.27**
	Built-up areas	3984.93	43.65	**197052.12**	3554.82	1675.53	6215.94	527.04	0.09	140.31	1291.41	**214485.84**
	Grasslands	447643.98	33433.56	26868.6	**1850337.63**	11487.87	270897.84	67316.58	1778.4	5635.8	92624.31	**2808024.57**
	Mines and quarries	1955.07	96.03	396.36	29002.95	**40253.22**	799.11	936.18	1.62	2988.18	1281.78	**77710.5**
	Natural woodlands	130713.93	19132.47	22713.48	374666.67	2002.95	**1560587.22**	46455.21	8064.99	4567.5	20476.89	**2189381.31**
	Plantations	4277.7	1612.17	3252.06	39988.62	419.85	55021.23	**643469.31**	12.87	224.28	3876.57	**752154.66**
	Shrublands	6014.07	5700.78	2601.54	21389.49	487.98	3722.4	789.48	**322.74**	227.88	385.02	**41641.38**
	Water bodies	255.69	926.01	37.35	2395.71	54.9	2805.84	220.32	6.93	**38151.9**	753.84	**45608.49**
	Wetlands	34473.78	387.09	508.5	15636.15	456.21	5406.48	5712.93	0.63	4663.8	**136969.2**	**204214.77**
	Total	**1792095.48**	**67543.83**	**260757.45**	**2440055.88**	**64710.63**	**1939256.82**	**769851**	**10199.43**	**59150.7**	**262225.26**	**7665846.48**

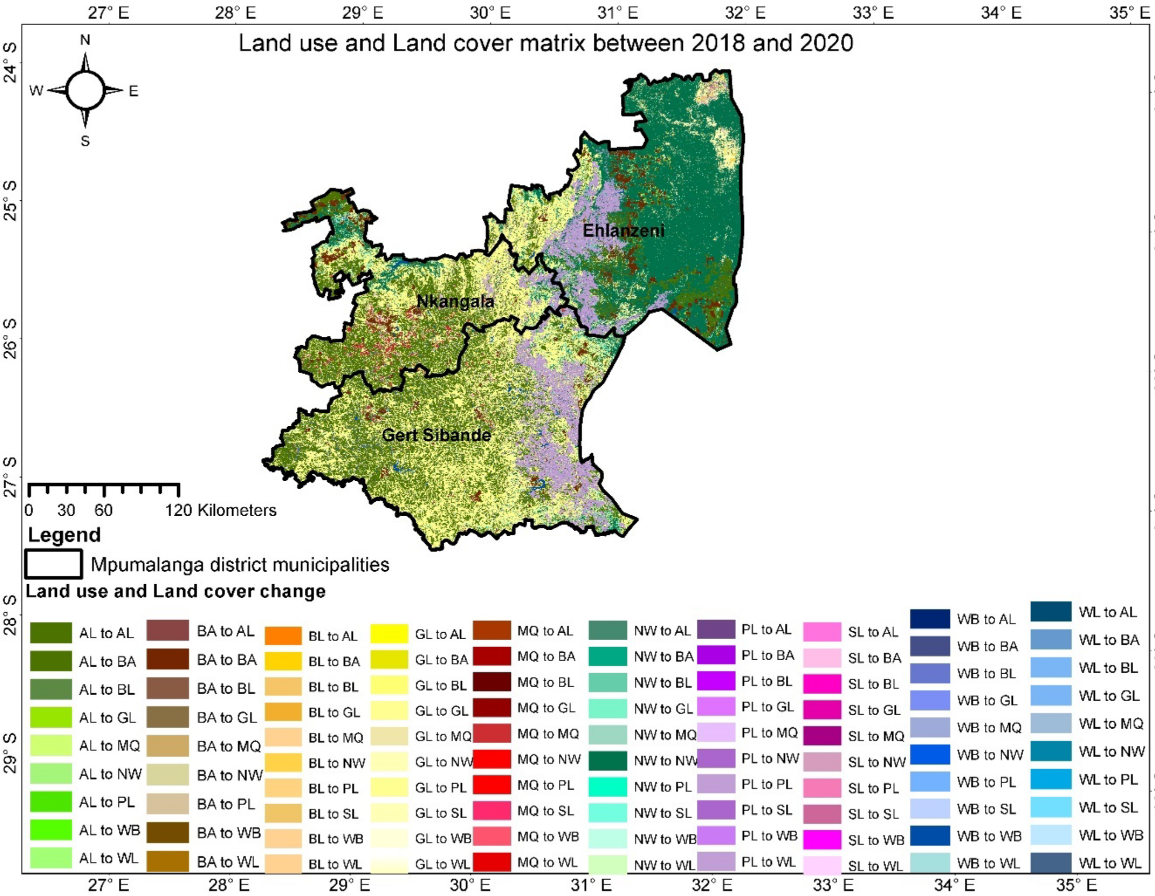


Figure 5.9: Land use and Land cover change matrix map between 2018 and 2020. *AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands*

Table 5.8: LULC change matrix between 2018 and 2020.

		Land class 2020											
	LULC Names	**Agriculture**	**Barelands**	**Built-up areas**	**Grasslands**	**Mines and quarries**	**Natural woodlands**	**Plantations**	**Shrublands**	**Water bodies**	**Wetlands**	**Total**	**Loss**
Land class 2018	**Agriculture**	**1764580.68**	159.75	1428.03	1710.63	4918.59	17416.71	1323.63		438.66	118.8	**1792095.48**	**27514.8**
	Barelands	1235.16	**22087.62**	262.53	26157.51	147.06	14352.21	526.32	14.04	974.43	1786.95	**67543.83**	**45456.21**
	Built-up areas	893.97	17.28	**250908.39**	4130.28	227.61	3670.74	712.8		41.94	154.44	**260757.45**	**9849.06**
	Grasslands	36123.03	10268.19	3558.78	**2152816.29**	4516.2	210795.39	16901.55	10.8	2161.62	2904.03	**2440055.88**	**287239.59**
	Mines and quarries	2162.43	74.79	433.17	11408.13	**49056.48**	225.36	137.97	1.17	1034.46	176.67	**64710.63**	**15654.15**
	Natural woodlands	9209.97	1515.15	3861	110974.23	105.93	**1804581.9**	6432.03	9	1005.75	1561.86	**1939256.82**	**134674.92**
	Plantations	2768.94	381.06	534.6	15095.43	595.08	964.62	**748509.84**	0.63	103.77	897.03	**769851**	**21341.16**
	Shrublands	3.06	18.36	3.6	1141.92	3.15	8999.37	2.52	**6.57**	3.6	17.28	**10199.43**	**10192.86**
	Water bodies	214.11	1074.15	43.29	3150.09	728.91	1254.69	124.11	1.98	**51503.58**	1055.79	**59150.7**	**7647.12**
	Wetlands	1721.88	123.3	93.42	2777.67	207.09	1486.53	1401.21	0.36	1274.04	**253139.76**	**262225.26**	**9085.5**
	Total	**1818913.23**	**35719.65**	**261126.81**	**2329362.18**	**60506.1**	**2063747.52**	**776071.98**	**44.55**	**58541.85**	**261812.61**	**7665846.48**	

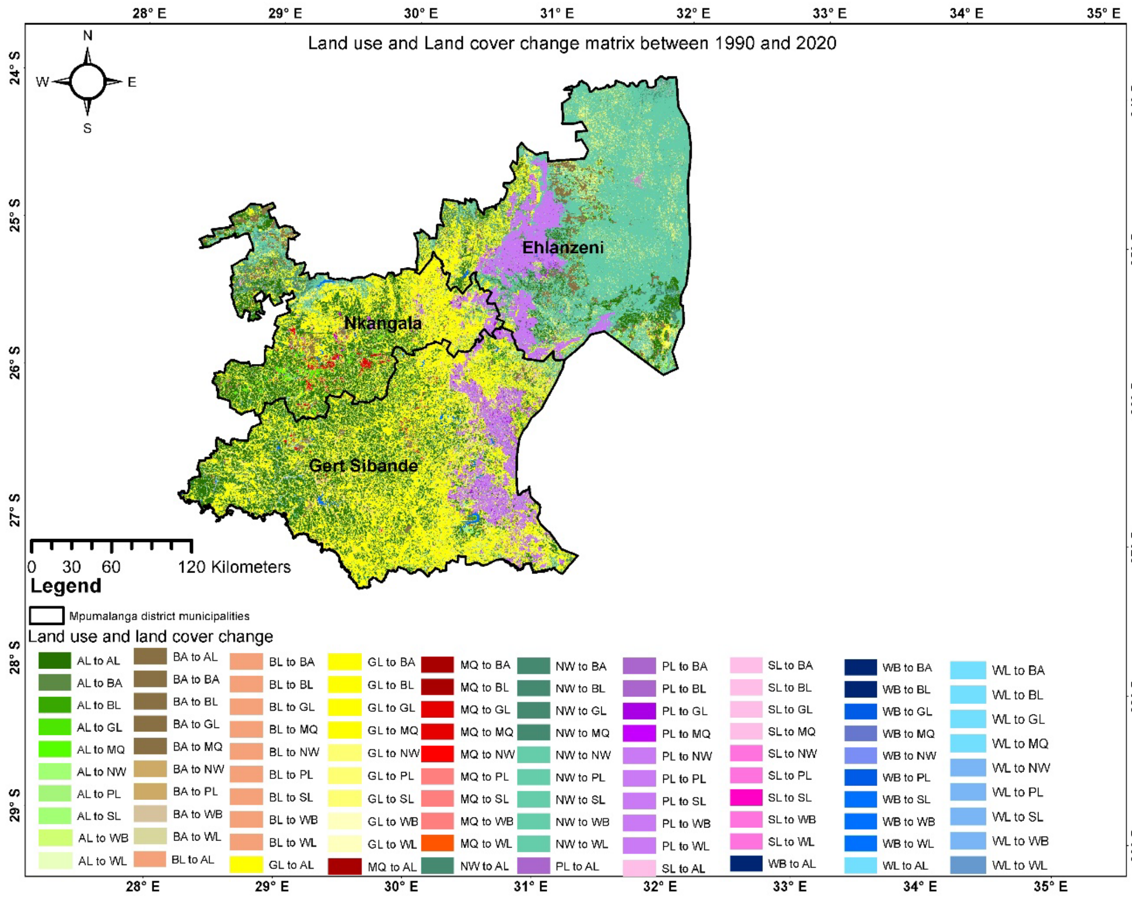


Figure 5.10: Land use and Land cover change matrix map between 1990 and 2020. *AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands*

Table 5.9: LULC change matrix between 1990 and 2020.

		Land class 2020										
	LULC Names	**Agriculture**	**Barelands**	**Built-up areas**	**Grasslands**	**Mines and quarries**	**Natural woodlands**	**Plantations**	**Shrublands**	**Water bodies**	**Wetlands**	**Total**
Land class 1990	**Agriculture**	**1303038.54**	919.17	9792.27	55433.16	23421.78	35049.87	11162.25	0.36	2381.85	2798.19	**1443997.44**
	Barelands	698.04	**1454.76**	710.01	4136.94	219.15	1901.34	177.48	0.9	1664.1	467.46	**11430.18**
	Built-up areas	4588.92	77.94	**157588.2**	5011.2	1381.59	7729.47	759.96		155.34	1691.64	**178984.26**
	Grasslands	355947.3	19277.37	47566.35	**1859284.8**	17460.18	332765.28	126810.18	6.21	9491.31	95368.68	**2863977.66**
	Mines and Quarries	1029.06	220.14	431.55	25838.73	**12593.7**	1502.28	1563.3	0.63	1659.42	1669.32	**46508.13**
	Natural woodlands	95288.49	6961.41	33160.05	233395.56	1433.7	**1592896.59**	25824.24	19.62	5222.25	21516.48	**2015718.39**
	Plantations	7812.81	1442.34	5476.14	51505.11	2693.79	63501.75	**601749.63**	3.69	679.59	8494.2	**743359.05**
	Shrublands	13967.64	3920.04	5103.09	45397.71	541.08	10015.56	2228.67	**7.11**	470.16	1685.25	**83336.31**
	Water bodies	287.82	886.41	110.34	3569.49	65.25	1260.99	282.51	2.07	**32994.27**	1452.06	**40911.21**
	Wetlands	36254.61	560.07	1188.81	45789.48	695.88	17124.39	5513.76	3.96	3823.56	**126669.3**	**237623.85**
	Total	**1818913.23**	**35719.65**	**261126.81**	**2329362.18**	**60506.1**	**2063747.52**	**776071.98**	**44.55**	**58541.85**	**261812.6**	**7665846.48**

5.3 IMPACT OF LULC ON WEF NEXUS

Over the past ages, Humans have altered the landscape for herding and hunting, clearing forests for settlements, infrastructures, resource extraction, and agricultural use (Kirch,2005; Ellis *et al.* 2013; Winkler, 2021). However, the extent, intensity, and rate of LULC Changes are far greater now than they were in the past (Hassan *et al.* 2016). As a result of the increasing human impact on natural resources, it has become clear that LULC changes are related to the serious environmental challenges. The demand for food, energy, and water is expected to increase further because of these shifting circumstances. Therefore, the need for collaborative and trans-disciplinary approaches to improve intergovernmental planning and coordination of government departments responsible for service delivery of these sectors cannot be overemphasized. This is where decision-support tools such as 'Nexus' come into play. A nexus approach is a systems-based approach that takes into consideration the inter-relatedness and interdependencies between sectors when considering projects, strategies, policy and investment options in complex socio-environmental systems. The following section will look at the impact of LULC changes on water-Energy Food (WEF) nexus.

5.3.1 Impact of LULC change on energy sources

In South Africa, coal mining is strongly tied with energy security since it provides 73% of the country's primary energy (Jeffrey, 2005). Most South Africa's coalfields, as well as the majority of coal-fired power plants, are in Mpumalanga (Mathu and Chinomona, 2013). The findings of the change detection show that considerable changes in Mining areas occurred during the 30-year research period (1990-2020). Mining and quarries grew in the Nkangala and Gert Sibanda districts between 1990 and 2020, as seen in figure 5.11. This is due to an increase in domestic demand for energy generation and fuel production, as well as an increase in local and worldwide demand. On the other hand, most natural woodlands in the Ehlanzeni area remained constant during the study period, although a significant loss was noted in the Nkangala district. This might be linked to mining activity in the Nkangala district, as well as the harvesting of fuelwoods, as the region is primarily rural. Mpumalanga has the most forestry plantations in South Africa, followed by KwaZulu-Natal. The Ehlanzeni and Gert Sibande districts represent Mpumalanga's forestry epicentre. Figure 5.11 shows that most forestry lands remained unaltered over the research period, with modest losses in Ehlanzeni and tiny gains in Gert Sibande. The severe drop in shrublands seen might be due to a complex interplay including increased human population, frequent drought, changes in settlement and land tenure patterns, and changes because of alien plant species invasion. Shrublands and woodlands are potential sources of renewable energy, therefore this might have a severe impact on energy sources.

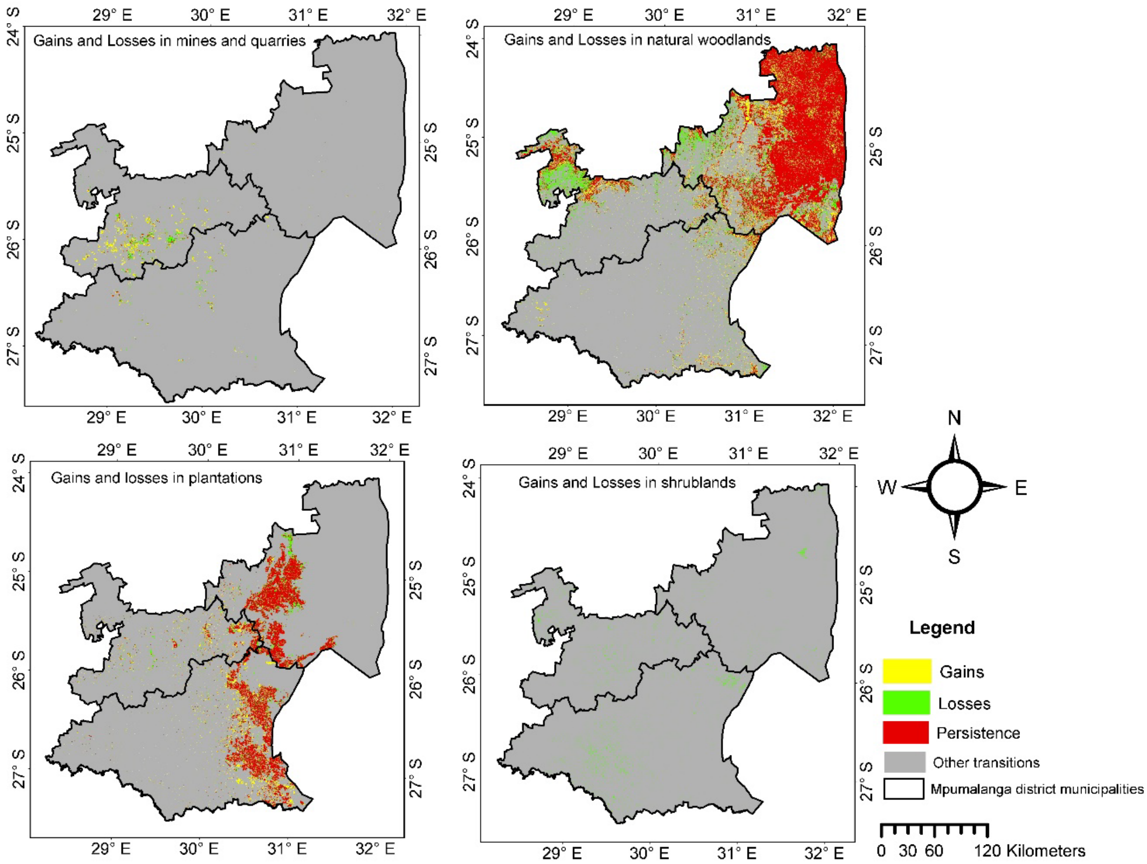


Figure 5.11: Land use types as a source of energy in the study area.

5.3.2 Impact of LULC change on food sources

The agricultural sector plays an essential role in stimulating economic development, supporting livelihoods, and securing food security for the people of Mpumalanga. The findings showed that the overall area of land used for agriculture, including both large- and small-scale farms, is approximately 181891.23 ha, representing 23.73% of Mpumalanga's surface area (7665846.48 ha). Commercial agricultural land in Mpumalanga comprised mainly grazing land and arable land. Grazing land is used for livestock and game farming, and arable land is used for crop production. Figure 5.12 shows that The Gert Sibande district accounted for the largest share of Mpumalanga's agricultural land, followed by Nkangala and Ehlanzeni. Regarding grazing land, 93,8% was in two districts, namely Gert Sibande (78,6%) and Nkangala (15,2%). It was interesting to notice that almost 90% of the arable land was in the Gert Sibande (61%) and Nkangala (30%) districts, which also had a high concentration of mining and quarries (Figure 5.12). The agricultural sector in Mpumalanga is dictated by several important drivers and processes of change affecting its ability to guarantee food security for the region. The LULC results shows the ongoing expansion of coal mines and their use of fertile land for mining operations. Considering this, a critical issue for food security is the extent of the mining-related threat to agriculture.

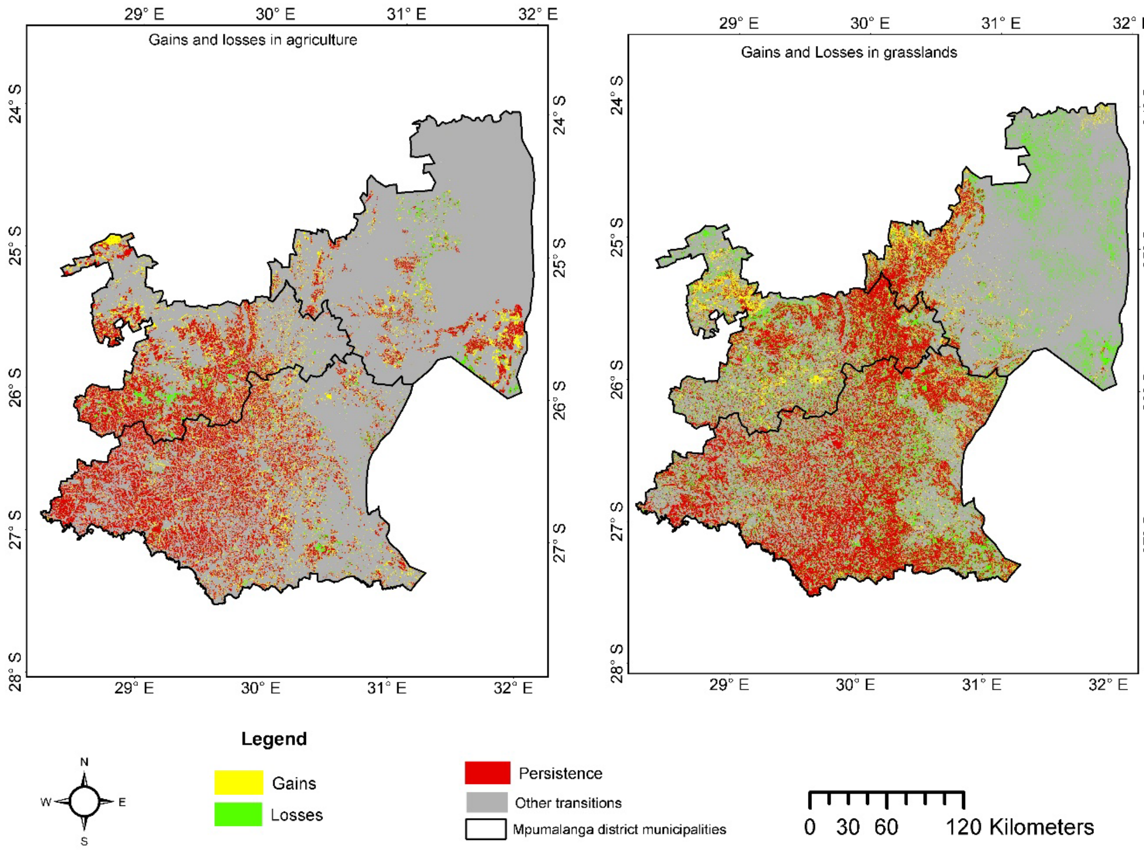


Figure 5.12: Land use types as source of food in the study area.

5.3.3 Impact of LULC change on water sources

It is anticipated that South Africa's water supply will not be sufficient to fulfill demand by 2025 based on existing usage patterns (Mnguni, 2020). Waterbody classes were more stable across the years of the analysis (Figure 5.13). There is also subtle increase in the wetland class. The Department of Human Settlements, Water & Sanitation has recognized the Upper Olifants Catchment, home to the eight coal mining activities, as one of South Africa's most stressed catchment regions in terms of both water quantity and quality. A thorough analysis of the water competition between agriculture and coal mining in Mpumalanga was published by Ololade *et al.* (2017). The analysis noted numerous issues, including the province's high level of irrigated farming operations and mining, which are causing the quality and quantity of water in the area to decline and are likely to have a negative effect on water security. Furthermore, water security in Mpumalanga is significantly impacted by the frequent draining of wetlands for farming, plantation forestry's influence on the water table, and poorly placed or managed open-cast mining's impact on the quantity and quality of water entering and exiting wetlands and rivers. Therefore, informed and least regret approaches to the use of natural resources, explicitly informed by a clear understanding of trade-offs, are essential for South Africa to have safe access to water and the ability to provide water for people and economic activity.

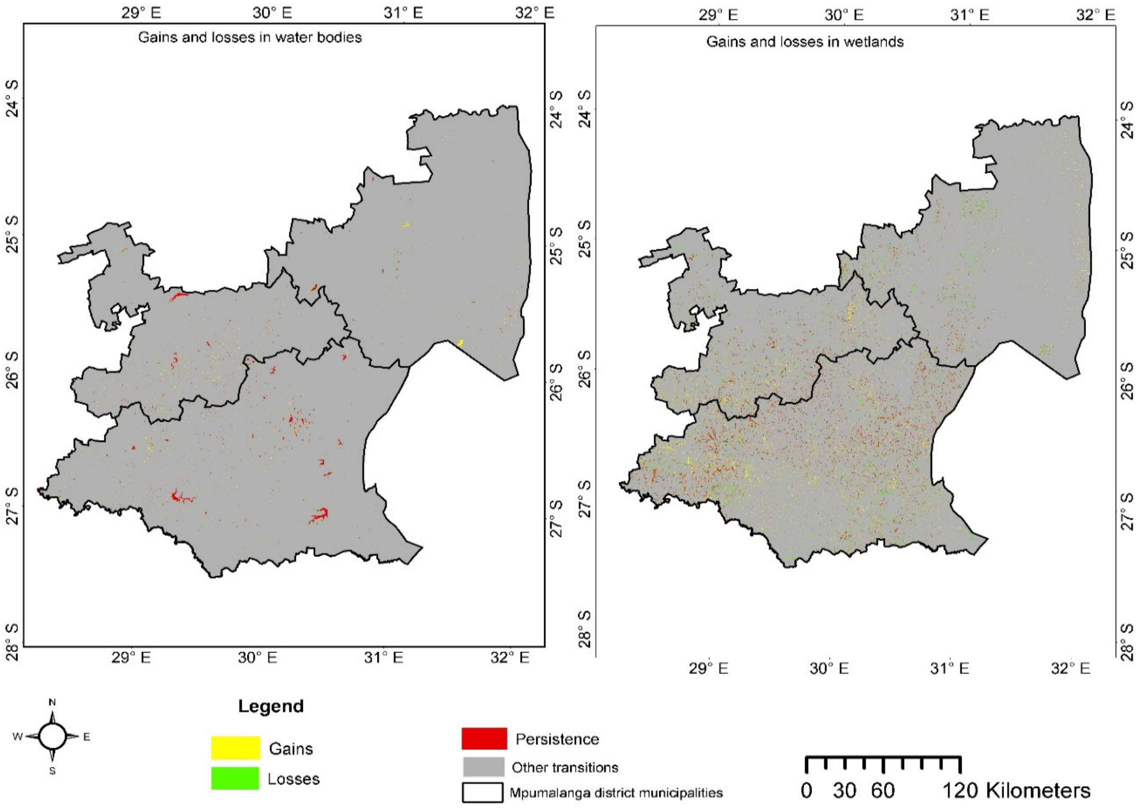


Figure 5.13: Land use types as a source of water.

5.4 MODELLING THE COMPLEMENTARITY BETWEEN EXISTING CLIMATE CHANGE INTERVENTIONS USING ENVIRONMENTAL AND SOCIO-ECONOMIC DATA

To minimize the trade-offs associated with climate change adaptation strategies, it is imperative to invest in new data collection methods (such as earth observations) and to create reliable and accurate models (Hallegatte, 2009; Camps-Valls, 2009; Biesbroek *et al.* 2020). Using remote sensing and machine learning, novel methodologies have been devised that estimate and predict desirable results as well as the relationships between variables while quantifying the level of uncertainty in these predictions and estimations (Holloway and Mengerson, 2018). Indeed, with advances in space information science and with an increasing use of computer applications in recent years, remote sensing and probabilistic machine learning has become powerful tools for analyzing nonlinear relationships and variable interactions to provide possible future scenarios and to inform decision-making processes (Ryo and Rillig, 2017). Therefore, the current study seeks to integrate remote sensing technology and probabilistic machine learning, in a view to develop a WEF nexus-based approach for sustainable adaptation that could help in the planning and implementation of adaptation interventions for cooperative governance in Mpumalanga. To achieve this, the model based on a generalized linear model (GLM) through logistic regression was implemented using 3 scenarios. Scenario 1: Model based on environmental variables only, Scenario 2: socio-economic variables (only) and final scenario: combining environmental and socio-economic variables.

5.4.1 Variable Importance

The P values and coefficients provide information about the relevance of the parameters that are measured by the model. P-values below 0.05 indicates significance or the estimates that are reliable. Therefore, Table 5.10, Table 5.11 and Table 5.12 shows the variables that could explain the location of the climate change adaptation projects and programmes.

Table 5.10: Significant variables and associated estimates for the model based on scenario 1.

Variable	Estimate	Std. Error	P-value
Intercept	4.5775749	1.9726762	0.020314 *
cdd_10	0.1132594	0.0426183	0.007872 **
cwd_10	-0.4995908	0.1444518	0.000543 ***
pH	-0.0643483	0.0272095	0.018034 *
Aspect	-0.0026298	0.0016217	0.104880
DEM	-0.0011952	0.0003913	0.002255 **
LULC_1990	-0.2508189	0.0960525	0.009021 **
LULC_2020	0.2694674	0.0877377	0.002131 **

Null deviance: 263.06 on 189 degrees of freedom, Residual deviance: 223.85 on 182 degrees of freedom, AIC: 239.85

Table 5.11: Significant variables and associated estimates for the model based on scenario 2

Variable	Estimate	St. Error	P-value
Intercept	1.087	0.5639	0.05380
Tribal_or	0.00001191	0.000003767	0.00157 **
Employment_rate	-4.649	1.962	0.01782 *

Null deviance: 263.06 on 189 degrees of freedom, Residual deviance: 251.43 on 187 degrees of freedom, AIC: 257.43

Table 5.12: Significant variables and associated estimates for the model based on scenario 3.

Variable	estimate	St. Error	P-value
Intercept	1.754	1.808	0.331799
cdd_50	0.08499	0.03225	0.008399 **
cwd_10	-0.6249	0.1614	0.000108 ***
Aspect	-0.003628	0.001724	0.035343 *
pH	-0.06814	0.02722	0.012304 *
LULC_1990	-0.2351	0.09913	0.017693 *
LULC_2020	0.2886	0.09082	0.001482 **
Tribal_or	0.00001746	0.000004138	0.0000245 ***

Null deviance: 263.06 on 189 degrees of freedom, Residual deviance: 214.64 on 182 degrees of freedom, AIC: 230.64

5.4.2 Misclassification error rate

To assess the summary of prediction outcomes, including both correct and wrong categorization issues, we made use of confusion matrices. The following aspects are shown by the segments of the confusion matrix: true Positives (TP) is the number of values that are predicted to be positive (location of the adaptation project or programme) and are therefore positive. True Negatives (TN) indicate cases in which the location is classified as the location of adaptation project or programme while there is no adaptation project or programme in the location.

The outcomes of the metrics employed in this study are discussed in the section that follows. The model-based confusion matrix for scenario 1 shows that 126 of 190 points are correctly classified by a misclassification rate of 33.68% (Table 5.13). On other hand, the testing data-based confusion matrix shows correct classification for 41 of 72 or misclassification rate of 43.06% (Table 5.16). The 120 of the 190 points in the model-based confusion matrix for scenario 2 are correctly classified, with a misclassification rate of 36.84% (Table 5.14). Conversely, the testing data-based confusion matrix for scenario 2 reveals that 51 from the total of 72 were correctly classified, for a misclassification rate of 29.17% (Table 5.17). According to the model-based confusion matrix for scenario 3, from the total of 190 points, only 133 were classified correctly, with a misclassification rate of 30% (Table 5.15). On the other hand, scenario 3's testing data-based confusion matrix indicates that 41 out of a total of 72 were correctly classified, indicating a misclassification rate of 43.06% (Table 5.18).

Table 5.13: confusion matrix with actual and predicted values and total error rate for the model-based scenario 1 (training data)

		Actual Values	
Predicted values		0	1
	0	60	33
	1	31	66
Total error rate =33.68%			

Table 5.14: confusion matrix with actual and predicted values and total error rate for the model-based scenario 2 (training data)

		Actual Values	
Predicted values		0	1
	0	56	35
	1	35	64
Total error rate= 36.84%			

Table 5.15: confusion matrix with actual and predicted and total error rate for the model-based scenario 3 (training data)

		Actual Values	
Predicted values		0	1
	0	63	29
	1	28	70
Total error rate =30%			

5.4.3 Goodness of fit

We used fit indices, such as the null and deviance residuals and Akaike information criterion (AIC), to assess the significance of the overall model. This test statistic determines if a model with predictors fits the data better than the model with simply an intercept (i.e. a null model). The test statistic shows the variation in residual deviance between the null model and the model with predictors. When P-value is very small, it means that the model is statistically significant. This means that all our models were statistically significant. The P-value for model-based scenario 1 is an exceptionally low 2.94×10^{-8}, P-value for scenario 2 is 1.78×10^{-6}, which is significant compared to the low P value. The P-value for the scenario 3 is 2.98×10^{-3}, which is greater than the P-values for scenarios 1 and 2, but the model is statistically significant since its p-value is less than 0.05.

5.4.4 Cut-off vs accuracy

The cut-off was used to classify the observations of the computed probabilities. The 3 graphs below show the classifier performance as the cut-off varies for each scenario. Interesting information is shown in each graph for each scenario. In scenario 1, the accuracy of the model grows until it reaches its maximum of 67.93% at the 0.55 cut-off point (figure 5.14). The accuracy of the model decreases just after 0.55 cut-offs. Figure 5.15 shows an erratic trend in the accuracy of the model for different cut-off values ranging from 0.345 to 0.766. It reaches the highest accuracy of 66.41% with the cutoff value of 0.54. Figure 5.16 illustrates how the accuracy of the model increases until it reaches its maximum of 69.08% at the cutoff value of 0.58. The accuracy of the model starts to decline at cutoffs of 0.58 and shows no signs of improving.

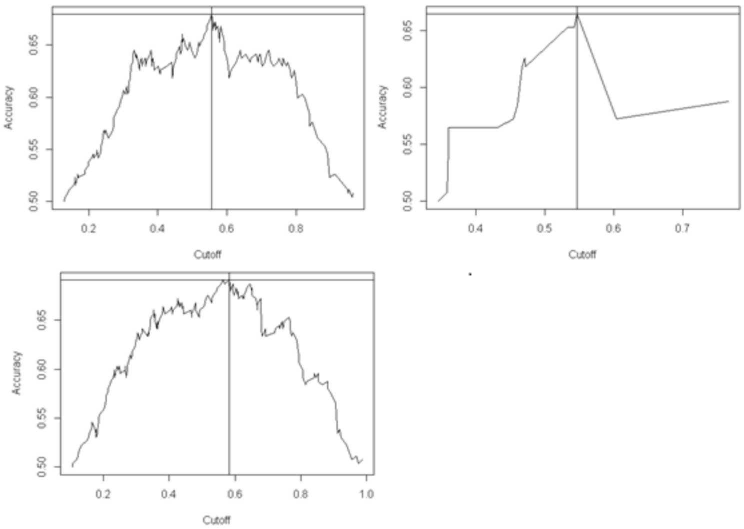
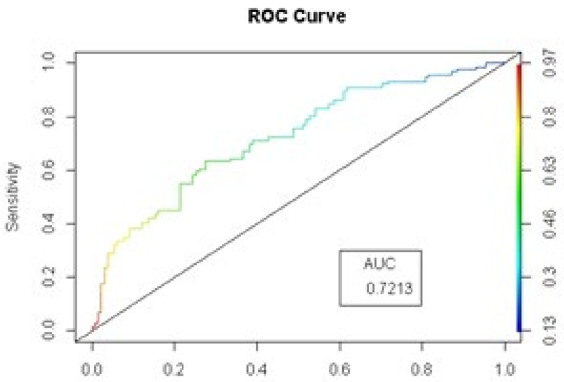
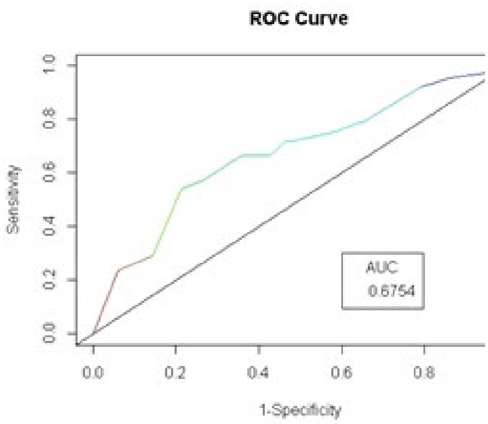


Figure 5.14(*Top Left*): accuracy vs probability cutoff (Scenario 1), Figure 5.15 (Top Right): accuracy vs probability cutoff (Scenario 2), Figure 5.16 (Bottom): accuracy vs probability cutoff (Scenario 3).

5.4.5 ROC vs AUC

We used the ROC and AUC to further evaluate the performance of the model. The Receiver Operator Characteristic (ROC) curve is an evaluation metric for binary classification problems. The Area Under the Curve (AUC) is a measure of the ability of a classifier to distinguish between classes and is used as a summary of the ROC curve. The higher the AUC, the better the performance of the model at distinguishing between the positive and negative classes. When 0.5<AUC<1, there is a high chance that the classifier will be able to distinguish the positive class values from the negative class values. When AUC=0.5, the classifier is either predicting random class or constant class for all the data points. The AUC of each of our models is more than 0.5, indicating that they can differentiate between 0 classes and 1 class.





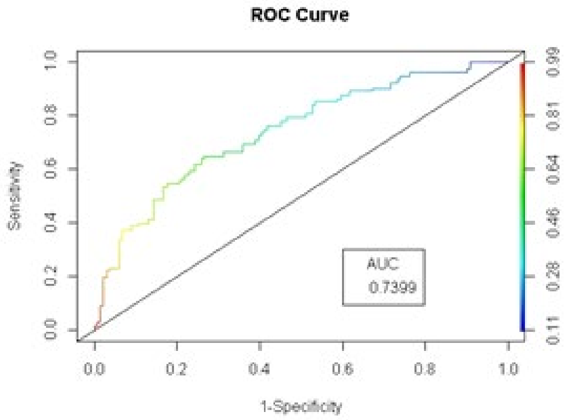


Figure 5.17 (*Top Left*): The ROC curve of the logistic regression based on scenario 1, Figure 5.18 (Top Right): Scenario 2 and Figure 5.19 (Bottom): Scenario 3.

5.5 Suitable locations for water or food-related projects and programmes

The spatial estimation map shows the areas where water or food-related adaptation projects can be implemented. The results of the spatial estimation show that the northern parts of Mpumalanga, particularly in the escarpment region, are the most ideal areas for implementing climate change adaptation projects. In addition, this region has also been identified as one among those areas where there is a potential severe loss of vegetation due to climate change. The spatial mapping results also showed that the western part of the Nkangala district municipality have a lot of potential for implementing water or food adaptation activities. This was interesting since Nkangala district is known as the busiest district in the province with the most potentially fertile land, but a larger portion is used for coal mining activities.

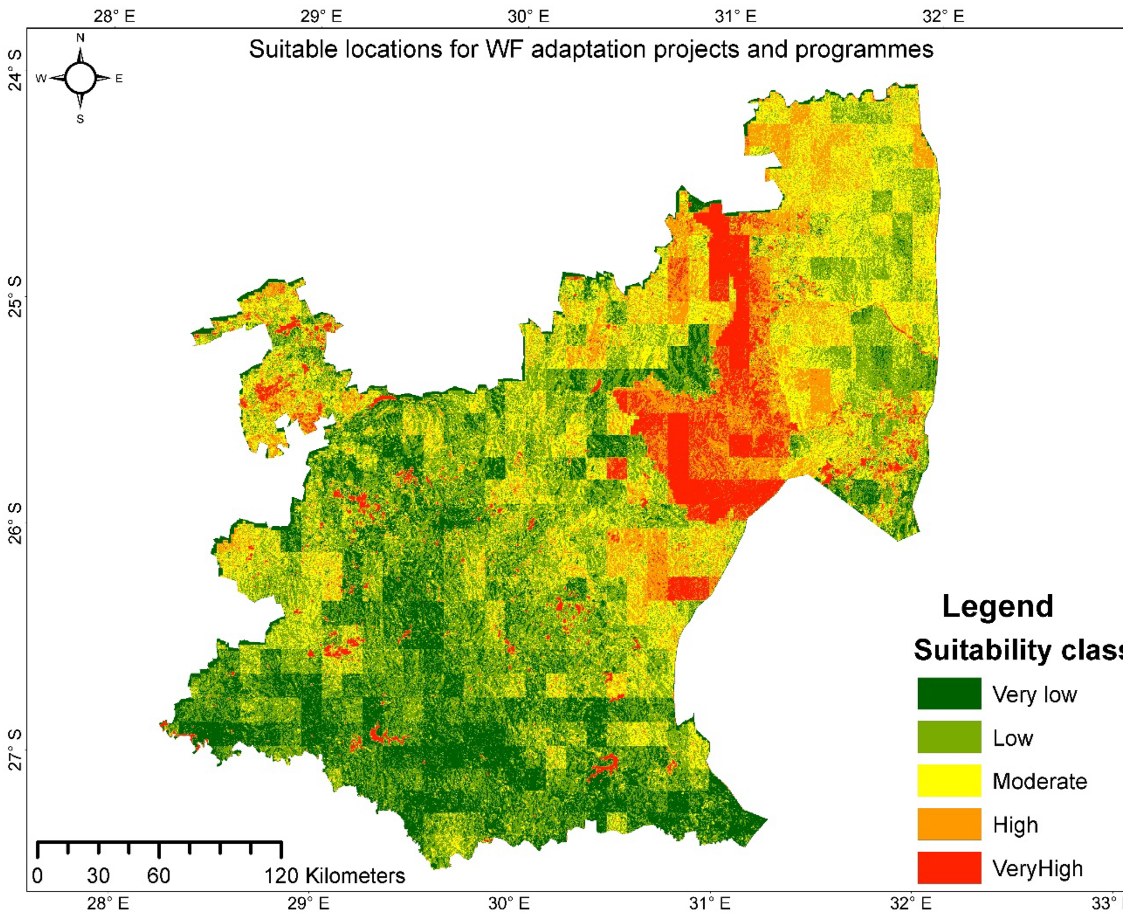


Figure 5.20: Suitable locations for water or food-related projects and programmes.

CHAPTER 6: NEW KNOWLEDGE AND INNOVATION

6.1 NEW KNOWLEDGE GENERATED USING GEOSPATIAL TOOLS

The project developed a geospatial visualization tool to visualize the products used and derived in this study. This tool included land use and land cover, extreme climatic variables, and topographic and soil variables. The modelling results were also be presented in this geospatial tool highlighting priority areas for climate change adaptation through the lens of water energy food nexus. This geospatial tool efficiently linked planning and implementation of scalable projects in Mpumalanga province. See the Geospatial Visualisation tool in Annexure 2.

This project was introduced at the launch of the COMPACT of Mayors in Mpumalanga (09-10 December 2021). It falls within the basket of climate adaptation projects for the province of Mpumalanga and introduces the application of geospatial modelling in the WEF nexus space. A collaborative workshop between the CSIR and the WRC on WEF the nexus was held at the CSIR's ICC, and proceedings are attached to this report as Annexure 1.

6.2. Wall-to-wall mapping land use mapping for the province of Mpumalanga

Wall-wall provincial maps showing changes in land use and land cover over certain periods of time; including the spatial location were analyzed using the WEF lens. This should enable departments responsible for the governance of the components of the WEF nexus to render services related to WEF to and for the communities in their jurisdictions more efficiently. The outputs of this project can also be used to identify and quantify arable land in Mpumalanga and provide projections of the size of populations that can be supported by natural resources (WEF) sustainably.

Through this project, a review paper on the bibliometric analysis of the WEF nexus in Africa (Chapter 2 of this report) has been published in the Sustainability Journal. In addition to the review paper, a conference paper has been submitted to the African Association for Remote Sensing of Environment (AARSE). This conference paper will be followed by a policy review paper and a paper focusing on "the spatial linkages of climate change adaptation projects or intervention with extreme climatic variables, other environmental and socio-economic variables". Finally, a MSc thesis will be submitted to the University of Pretoria in 2023.

CHAPTER 7: CAPACITY BUILDING, KNOWLEDGE DISSEMINATION & TECHNOLOGY TRANSFER

A MSc student and a Postdoc, both based at the University of Pretoria, contributed to this project. The postdoc, Dr Omolola Adeola, was instrumental in the writing of the comprehensive review of the published scientific review paper. While Mr. Wongalethu Silwana, the MSc student, focused on the thesis development focusing on land use land cover change and climate change adaptation through the lens of WEF. His work was directly linked to this project.

7.1 POST-DOC STUDENT'S CONTRIBUTION TO THE PROJECT

The postdoc, Dr Omolola Adeola was associated with the Centre for Environmental Studies. She led the comprehensive literature review, based on bibliometric analysis, focusing on climate change adaptation through the lens of water energy food (WEF) nexus published in a "Sustainability journal". This review paper served as a critical input to the final report, in Chapter 2. Below is the abstract of the paper:

"Access to clean water, reliable energy services and adequate food supply are basic needs for life and contribute to the reduction of national and global levels of human poverty and forced migration. This study concentrated on reviewing progress made in understanding the relationship between the Water-Energy-Food (WEF) nexus and climate change adaptation, using Africa as a case study. The method used to achieve this objective was the bibliometric analysis, covering the period from 1980-2021. Data used for this study were acquired from the Web of Science (WoS) and Scopus databases. Initially, 95 documents were retrieved from the WoS and Scopus core collection databases, but 30 duplicates were removed, and 65 documents were used. The outputs were further analysed using the bibliometric R package and VOSviewer. Analysis of the top 100 keywords in the 65 publications that link WEF nexus with climate change adaptation for Africa showed that 46 keywords fall under the application of WEF nexus, 31 key-words under the implementation of WEF nexus and 23 keywords under the implication of WEF nexus. Researchers from countries around the world have published the WEF nexus work undertaken on the African continent. Countries with the highest number of publications were South Africa, the United Kingdom, the United States of America, Germany, Kenya and Zimbabwe. Thematic analysis was used to explore the conceptual structure of WEF publications, and it produced four themes: (i) well-established concepts appropriate for structuring the conceptual framework of the field of WEF nexus in Africa; (ii) strongly developed concepts but still marginal for the field of WEF nexus in Africa; (iii) not fully developed or marginally interesting concepts for the field of WEF nexus in Africa, and (iv) significant cross-cutting concepts in the field of WEF nexus in Africa in relation to climate change adaptation. This study contributes to the growing body of literature on the WEF nexus by pointing out dominant themes from those that are still emerging in the scholarly work done in Africa."

7.2 MSC STUDENT REPORTS AND OTHER DELIVERABLES

The MSc student Wongalethu Silwana is registered with the University of Pretoria, in the Department of Geography, Geoinformatics and Meteorology (GGM). He registered MSc in Geoinformatics.

- He presented the conference paper entitled "*Analysis Of Land Use and Land Cover Change Dynamics and Its Impacts On WEF Nexus Resources Over A 30 Year Period*

(1990-2020) In Mpumalanga, South Africa" at the African Association on Remote Sensing of Environment (AARSE) (AARSE 20202) in October 2019 held at Kigali, Rwanda. The conference paper has been selected to form part of the "Book Chapter" to be organized and published through "Springer" (See Annexure 3 for Abstract).

- Locally, he presented his work at the Climate Change Research Conference hosted by the City of Tshwane the 9-10 March 2023 (See Annexure 3 for Abstract).
- He is now finalizing his thesis to be submitted for examination in June 2023.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL DISCUSSION AND IMPACT SYNTHESIS OF THIS PROJECT

This project contributes to the growing body of literature on WEF nexus. It broadens the perspectives that exist in literature on the WEF nexus by linking the WEF nexus concept with climate change interventions and climate sensitivity at the provincial level. The tools used in the study are anchored in geospatial techniques and have been used by many authors that are running similar studies. The outputs of the study are pragmatic and readily usable for land management decisions.

It is evident that LULCC occurred in the last 30 years in Mpumalanga province. The LULCC was synthesized through the lens of WEF. For example, there has been increase in mines and quarries, and agricultural indicating a potential of the demand for water, energy and food. Extreme climatic variables as indicator of climate change were analysed, indicating consistent potential of drought impact in the province. LULCC and extreme climate variables were related to the climate change adaptation intervention categorised through the lens of WEF in the province as recorded in the DFFE's NCCRD database. When the database was analysed through the lens of WEF, it was clear that more climate change adaptation interventions were related more towards water and food, than energy. Further analysis was done to understand the drivers of the location of the climate change adaptation interventions or actions spanning from environmental to socio-economic drivers. Using the understanding of the drivers using advanced statistical analysis, a framework or model to synthesise and prioritise potential areas of climate change adaptation intervention or action in Mpumalanga (see 5.19).

In terms of the synthesis of the project impact, the project ideas and results were shared with several stakeholders through participation in various workshops arranged by WRC, Mpumalanga Provincial departments and Tshwane Metropolitan. These were some of the highlights for impacts:

- Updating climate change adaptation intervention or actions in DFFE's NCCRD database targeted to WEF. This will contribute the climate change adaptation and WEF discourse in the country with direct contribution to the South African's National Climate Change Adaptation Strategy.
- Use of the geospatial tools in the synthesis and understanding of climate change adaptation through the lens of WEF contributes to the exploitation of Space Science and Technology, including 4IR for societal relevance as part of the "White Paper on Science, Technology and Innovation" and the recently approved DSI's Decadal Plan.
- The project help stimulates critical thinking on aligning the sustainable development goals (SDGs) with planetary boundaries in the post-2015 development agenda.
- This project will help in the systemization of planning and decision making at provincial level to support sustainable adaptation by maximising synergies and minimising trade-offs in resource use and enhancing policy coherence across the WEF sectors.
- The project enhanced the current national adaptation policy landscape by not only improving the efficiency of resource use among the WEF nexus sectors but provides a broader view of impact of resource use and management on the overall environment and societal well-being.

8.2 CONCLUSIONS AND RECOMMENDATIONS

Conclusions based on each study aim are as follows:
The first aim was to analyse the measures on climate change adaptation, seen through the WEF nexus in the Province of Mpumalanga. The study contributed to, and updated, the National Climate Change Response Database (NCCRD). The NCCRD is hosted by SAEON and is managed by DFFE. This project contributed to the NCCRD by uploading climate change adaptation projects and programmes or interventions. The interventions were classified through the lens of WEF. Sectors dominating these interventions were water and food. Energy projects / interventions were limited.

The second aim was to highlight the significance of provincial government in the interplay between governance initiatives on the WEF nexus and climate change adaptation. As a response, we focused on showing the climate change adaptation interventions through the lens of WEF as updated in the database, in relation to land use and land cover as well as the extreme climatic variables. It was evident that more interventions were associated with areas of extreme climatic variables (e.g. drought-related). Though, there was land use and land cover change, these were not associated specifically with climate change adaptation interventions.

The third aim was to describe and analyze the influence and the confluence of current climate change adaptation planning at a provincial level with the WEF nexus. Here we focused on the drivers of climate change adaptation interventions. We analysed environmental, land use – land cover (1990-2020) and socio-economic variables in relation to climatic change adaptation and most of the environmental variables explained the location of the interventions.

The fourth aim was to facilitate an informed and coherent implementation of WEF nexus measures to enhance the effectiveness of implementing climate change adaptation measures. As a response we used the drivers (environmental, and socio-economic) of climate change adaptation and machine learning techniques to develop areas of potential climate change adaptation interventions.

Recommendations stemming from this are:
- There is a need to acquire and update energy-related climate change adaptation interventions for Mpumalanga for a complete WEF nexus synthesis.
- There is scope to upscale the coverage of the analyses done in this project to reach other provinces.
- The upscaling of this project should aim to cover the whole country.

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ANNEXURES

Annexure 1: Workshop report: strengthening the research-policy-practice interface for the WEF nexus in South Africa

Date: 09 September 2022
Venue: CSIR International Convention Centre
Time: 09:00-15:00
Participants (not listed)

Introduction

- The Water-Energy-Food nexus is a developing phenomenon with multiple descriptions, currently anchored in the academic environment.
- At the Water Research Commission, the Water-Energy-Food nexus has been transformed from a 'lighthouse' into a research programme.
- Over the next 10 years, focus will be on translating the WEF nexus concept into policy as well as human and institutional capacity development.
- Furthermore, part of the objective is to translate WEF nexus into practical or applicable solutions for South Africa, in the context of the impacts of climate change.
- The Water Research Commission is committed to fund the WEF nexus research and promote communication among researchers, who are in turn tasked to turn academic outputs into a policy framework for WEF nexus.
- Part of the intention is to bring the business sector on-board, based on tangible deliverables.
- It was noted that the invited speakers from the Energy and Food sectors were not present at the workshop.

Key takeaways from the scope of the workshop:

(i) **Interpretation /translation of the WEF concept for use in policy formulation/ development.**

(a) options for socializing the WEF concept in the relevant SA policy landscape
   - There is no common understanding of what WEF nexus really means.
   - In the social sciences, WEF nexus is perceived as a 'splintered discourse', which is heavily reliant on science. Without addressing social issues, WEF nexus is not addressing systemic barriers in society.
   - Social sciences should be part of policy making through:
     - Political transformations – integrated policy planning.
     - Acknowledging customary approaches in resource use – e.g. recognize traditional ways in which water is managed.
     - Localising WEF models and frameworks: all use different indicators; overlay social participatory approach.
       - Participatory scenario development: acknowledge all different role places; develop different scenarios; broad-based support.

(b) WEF nexus in the current policy landscape of SA

- WEF nexus does not appear in various policies such as the Water Resource Strategy. It is expected that the same observation is true for Energy and Food-related policies, in addition to Water.
- Policies on water, energy and food are led by different national departments which do not necessarily communicate with each other on strategic approaches.
- In South Africa, it matters who presents the WEF nexus concept to stakeholders. There are key people who should be targeted in national departments – e.g. those responsible for coordinating the transboundary work. Furthermore, the WEF nexus should be more directly linked to climate change, biodiversity and health issues where communication channels are already well established up to the level of Ministers.

(c) anchoring the WEF nexus in the SA policy landscape

- Political principals (at various levels) and communities on the ground need to be engaged through various platforms to enrich their knowledge about WEF nexus.
- A 'champion' organization is needed to advance the translation of WEF nexus from research into policy and practice.
- What is needed for WEF nexus is scaling: *scaling up* (impact laws and policies); *scaling out* (impact to greater numbers) *scaling deep* (changing mindsets of individuals, institutions, etc.).
- Communication between relevant national government departments responsible for policies of these natural resources.

(ii) **The practice of the WEF nexus in South Africa.**

(a) How and where has the WEF been implemented in South Africa?

- Research has largely been undertaken by research institutions, particularly universities such as UKZN, UP and research institutions such as the CSIR.
- In the water space, research has largely focused on the catchment areas such as Usuthu-Inkomati.
- The practice of irrigation for farming purposes was highlighted as one of the key examples of where the WEF nexus is in practice. Farmers are already practitioners of WEF nexus without that label being associated with them. In practice, WEF nexus starts at household level! Generally, people are aware resource constraints and how resources interconnect.
- Another key example of the application of WEF nexus in South Africa is on mine closure. About 640 mines are deserted (which create well known problems); mining institutions own vast amounts of land which they would like to use for food production. The state is apparently planning to develop a task force to protect these derelict mines at a cost of more that R600 million.
- Progressive institutions such as the Landbank, Nedbank etc. are showing interest in the WEF nexus space, but demonstrable evidence which is hindered by lack of adequate data is slowing the engagements.

(b) Main learning from implementing the WEF nexus in South Africa

- research institutions are still operating in silos. This is also applicable to national departments responsible for policies on water, energy and food – considering the cross-cutting nature of these natural resources.
- South Africa does not have business-orientated proposals for the private sector to invest in.
- Need to consider optimum combinations of time and space to optimize the uptake of WEF nexus.

(c) challenges and opportunities for the implementation of the WEF nexus in South Africa.

Challenges

- lack of integration between social sciences and the 'other' scientific approaches.
- human and institutional capacity.
- general perceptions of WEF nexus as an academic exercise. Verry little or no evidence exists on the ground.
- data availability and models (analytical, social, etc.) applicable at various scales.
- silo operations in the WEF space and lack of adequate funding.
- hundreds of publications available, but do not translate into practice.
- lack of case studies and capacity at operational level.
- disagreements in where the constraints are in WEF nexus – are they in water or energy sectors?
- there will still be gaps of a financial muscle being used to influence the WEF nexus agenda.

Opportunities

- embed WEF nexus into existing academic modules and curricula.
- 46 WEF models recently documented, 61% are not accessible.
- 'winter' schools and short training courses on WEF nexus.
- capacity-building at various levels of governance – from local to national.
- increased funding opportunities from the WRC.
- partnerships between the public and private sectors – these need business case studies for the transition to practice.
- mapping of WEF nexus methodology and interlinkages with socio-economic growth and development issues can be an entry point into commercial agriculture. This will also provide opportunities for emerging farmers to be provided with government subsidies.
- introduction of geospatial capability in the WEF nexus.
- SADC has adopted nexus as a tool for Natural Resource Management. However, South Africa is yet to develop its own WEF nexus steering community of community of practice.

Conclusions

1. WEF nexus is a tool – a means to an end. Various sectors need to work together. There are tools to compare tradeoffs in the WEF sectors.

2. More case studies are needed in South Africa to attract both political and business leaders.
3. Need to recognize, acknowledge, and incorporate indigenous knowledge systems in the scientific WEF nexus research.
4. South Africa need to develop a policy on WEF nexus. That policy should unpack the transition in between research-policy-practice.
5. Platforms on WEF nexus are needed country wide to accommodate a variety of stakeholders.
6. There are six (6) catchment management forums that meet quarterly – perhaps we need to propose having a slot to present the WEF nexus research. The latter will need a champion, and at this stage, it may be the WRC, who pushed the challenge back to the researchers. In addition to this proposal, establishment of a national WEF forum is proposed.
7. Towards the development of a business/investment case for the WEF nexus, forward-looking scenario planning is critically important. The business sector would like to see upfront how they stand to benefit from the application of nexus (see the **WRC report 2711/1/2021** for an example if scenario report).
8. A synthesis report on the WEF nexus done to-date is necessary.
9. Social scientists are needed in the WEF nexus to transform policy briefs and ministerial reports (prepared by the WRC) into practice.
10. The private sector needs to be more directly engaged. One way of approaching this is to support through the WEF nexus research, their business aspirations. One needs to be in the space and speak the business language in order to receive attention and make an impact.
11. Having a baseline and context are very, very important in designing initiatives around WEF nexus: need to have the correct premise, relevance, awareness of resource scarcity, poverty, climate change, indigenous knowledge systems, end-users, socio-economic rights in the country, data availability and research methods, institutional capacity, etc. Microsoft Excel based models developed by some of the participants present at the workshop need to be put to the task, through provision of more data to enable the Monitoring and Evaluation of their efficacy.
12. Finally, a champion is needed to drive WEF nexus platform into areas of political and social influence; focus on advantages that only WEF nexus can provide; and attract the business sector into the WEF nexus research space.

Annexure 2: Link to the geospatial visualization tool

This is a web-based system used to visualise the spatial datasets used and derived in this study. It is developed using ArcGIS Pro, and ArcGIS online capability. The variables names as appeared in the web visualisation are listed and described in Table A2.1

.

Variables	Resolution/scale	Geospatial Web-Viewer (Names)	References
Climate change adaptation projects and programmes	-	Spatial Distribution of Adaptation Projects	https://nccrd.environment.gov.za/submissions/new/CA35433E-F36B-1410-8684-00528B626FB9
Hotspot (hotspot analysis based on the total CC intervention points)	30 m	Hotspot	**This study**
Suitable areas for Water and Food projects, Energy was not considered because		Suitable Projects	**This study**
Soil properties	250 m	Coarse Fragments(cm³/dm³), Silt (g/kg), Sand(g/kg), Bulk Density(cg/m³)), Clay Content(g/kg), Cation Exchange at pH7 (mmol(c)/kg, Nitrogen (cg/kg), Soil Organic Matter(dg/kg), pH (ph*10)	https://soilgrids.org/
Topographic information (derived from the DEM)	30 m	Elevation, Slope (%) and Aspect(°)	https://earthexplorer.usgs.gov/
Land Use and Land cover dataset	Sentinel – 20 m Landsat – 30 m	Mpumalanga 1990, 2014, 2018	https://egis.environment.gov.za/data_egis/data_download/current
Socioeconomic data (education levels, settlement type, employment status, income levels, Population)	-	Income levels, Education levels, Employment Status, Settlement types	Statistics South Africa 2011
Mpumalanga administrative boundaries	-	Mpumalanga District Municipalities Mpumalanga Local Municipalities	http://www.sasdi.net/metaview.aspx?uuid=a227be54418cf2cf678bc933accff10e,

Climate indicators	8 km	See variables starting with 1p5 projections….	https://greenbook.co.za

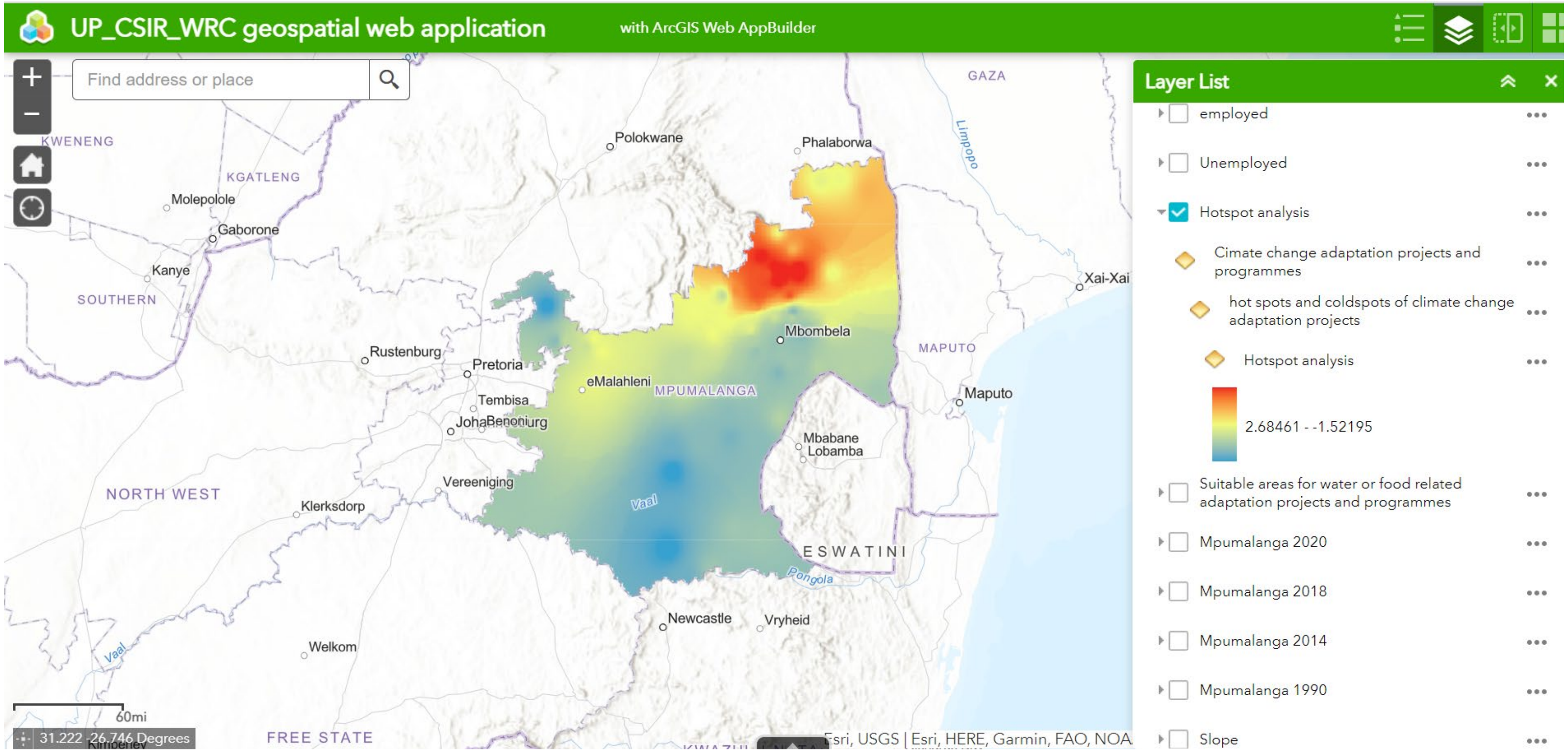

Figure A2.1: The geospatial visualisation tool can be accessed through this link:

https://uparcgis.maps.arcgis.com/apps/webappviewer/index.html?id=1f8cbb0678574e549a900378b68a7158

(*if you encounter any challenges to visualise this, please contact the corresponding author of this report*)

Annexure 3: Scientific outputs (Abstracts) by MSc student

The abstract below was orally presented at the International Conference, African Association of Remote Sensing of Environment (AARSE) conference in October 2022, Kigali, Rwanda.

ANALYSIS OF LAND USE AND LAND COVER CHANGE DYNAMICS AND ITS IMPACTS ON WEF NEXUS RESOURCES OVER A 30-YEAR PERIOD (1990-2020) IN MPUMALANGA, SOUTH AFRICA

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Abstract
Developing countries face a difficult challenge in meeting the growing demands for water, energy, and food (WEF), which is further amplified by the rapidly land use and land cover s changes (LULCC). This study used Land use and land cover (LULC) derived from the South African National Land Cover Data repository for 1990 and 2020 datasets in deepening an understanding of the impact of LULCC on WEF nexus resources. Between 1990 and 2020, mines & quarries and built-up areas increased by 30.19% and 40.89%, respectively. The transition matrix based on post-classification comparisons shows that 12.42% of grasslands in 1990 were converted into agriculture in 2020. The observed LULCC dynamics were attributed to socio-economic growth and extreme climate events. This approach had various advantages (e.g. understanding WEF nexus change dynamics in a spatial-explicit manner), and providing a novel methodology that enables collaborative assessment of nexus resources with respect to the environment.

Keywords: Land use and land cover; Water-energy-food nexus; Sustainability

The abstract below was orally presented at Climate Change Workshop at Tshwane, March 2023.

SCENARIO MODELLING TO SUPPORT STRATEGIC PLANNING AND IMPLEMENTATION OF CLIMATE CHANGE ADAPTATION INTERVENTIONS FOR COOPERATIVE GOVERNANCE IN MPUMALANGA

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Abstract
It is not yet clearly understood how the adaptation concept can be applied to ensure water, energy and food (WEF) security nexus. Therefore, there is a need to comprehend the role of WEF nexus in adaptation with the aim of enabling the design, development and implementation of effective adaptation policies and strategies. The current study successful

supported updating the National Climate Change Response Database (NCCRD), adding around 141 adaptation focused projects and programmes to the database, and mapping them according to the districts in the Mpumalanga province. We proposed the use of machine learning and geospatial modelling tools to identify areas where water, energy, or food projects should be implemented. This was achieved by creating scenarios that combined topographic measures, extreme climate events, soil characteristics, socioeconomic factors, and Land use Land cover (LULC) change. Scenario 1: Model based on environmental variables only; Scenario 2: socio-economic variables and final scenario: combining environmental and socio-economic variables. The analysis indicated that water, energy and food resources are already under increasing pressure from climate change, land use and land use competition. This highlighted the need for comprehensive and integrated approaches to adaptation, such as WEF nexus, which takes into consideration the inter-relatedness and interdependencies between sectors when considering interventions, strategies, policies, and investment options in complex socio-environmental systems. This approach also offered a novel methodology that gave an idea of the number and scope of adaptation projects required to strike the balance in the WEF tradeoffs. This is essential to increase the effectiveness of planning and implementing climate change adaptation measures to prevent maladaptation.

Keywords: *Adaptation to climate change; WEF nexus; sustainability*