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**DEVELOPING A WATER-ENERGY-FOOD (WEF) NEXUS-BASED APPROACH  
FOR SUSTAINABLE CLIMATE CHANGE ADAPTATION INTERVENTIONS: A  
CASE STUDY OF MPUMALANGA PROVINCE**

By

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## M.SC DISSERTATION

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### **ABSTRACT**

The challenge of meeting the growing demands for water, energy and food is further complicated by the impact of climate and land use land cover (LULC) change. The Mpumalanga Province where agricultural production compete with coal mining for land and water consumption is a prime example of challenges involved in sustaining the water, food, and energy. A more holistic understanding of LULC can help in managing competing land use objectives, leading to improved climate change adaptation strategies. The Water-Energy-

Food (WEF) nexus is an effort to address challenges affecting WEF sectors by taking into consideration the inter-relatedness and interdependencies between these sectors to balance their perspectives and management. As a result, this study aimed to undertake a pragmatic approach that is based on geospatial analytical methods to support WEF nexus climate change adaptation in South Africa's Mpumalanga Province. To achieve this, the study investigated the impact of LULC change on WEF resources by analyzing South African National Land Cover (SANLC) data from 1990, 2014, 2018 and 2020 using Geographical Information Systems (GIS) and remote sensing techniques. The study also located the recently completed and on-going adaptation projects that contribute to the WEF nexus in the study area. As such, the logistic regression model was implemented using three scenarios to understand the drivers of the location of the WEF nexus based-climate change adaptation interventions or actions spanning from environmental to socio-economic drivers. Scenario 1: Model based on environmental variables only; Scenario 2: socio-economic variables only and scenario 3: combining environmental and socio-economic variables. Based on the understanding of the drivers and spatial estimation, a framework or model was developed to synthesize and prioritize potential areas of climate change adaptation intervention or action in Mpumalanga Province. The results of LULC change over the study period (1990 – 2020) show that the LULC areas under agriculture, built-up areas, mines and quarries increased from 18.84%, 2.33%, 0.61% in 1990 to 23.73%, 3.41% and 0.79% in 2020, respectively. While grasslands have decreased from 37.36% in 1990 to 30.39% in 2020. All of these changes have a direct impact on water supplies, energy sources, and food production. It was evident that more interventions were associated with areas of extreme climatic variables (e.g., drought related). All models were statistically significant, with Area Under the Curve (AUC) = 72% for scenario 1; 67% for scenario 2 and 73% for scenario 3. The results of the spatial estimation revealed that the northeastern region and northwestern region of the Mpumalanga Province should be prioritized for adaptation interventions. This work provided a broader view of the impact of resource use and management on the overall environment and societal well-being. The results obtained from this study indicate that the use of geospatial tools can be beneficial in the planning and prioritization of activities related to climate change adaptation.

## RESEARCH OUTPUTS

### 1. Conference proceedings and book chapter

- (i) Wongalethu Silwana, Abel Ramoelo, Philemon Tsele, Brian Mantlana and Oscar Mokotedi. *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*. This paper was presented at the African Association on Remote Sensing of Environment (AARSE) (AARSE 2022) in October 2022 held at Kigali, Rwanda <https://aarse2020.org/>. The conference paper has been selected to form part of a “Book Chapter” to be organized and published through “Springer”.

### 2. Publications

- (i) Omolola Adeola, Abel Ramoelo, Brian Mantlana, Oscar Mokotedi, Wongalethu Silwana and Philemon Tsele (2022). *Review of publications on the Water-Energy-Food nexus and climate change adaptation: a case study of Africa*. Sustainability Journal. <https://doi.org/10.3390/su142013672>.

### 3. Published project report

- (i) Brian Mantlana, Oscar Mokotedi, Abel Ramoelo, Wongalethu Silwana and Philemon Tsele (2023). *The Water-Energy-Food nexus as the catalyst to enhance cooperative governance for climate change adaptation in South Africa*. Available from: <https://www.wrc.org.za/wp-content/uploads/mdocs/3092%20final.pdf>

### 4. Presentations

- (i) Wongalethu Silwana, Abel Ramoelo, Philemon Tsele, Brian Mantlana and Oscar Mokotedi. *Scenario modelling to support strategic planning and implementation of climate change adaptation interventions for cooperative governance*. The scenario modelling results were presented at the Climate Change Research Conference hosted by the City of Tshwane and Tshwane University of Technology (TUT) on the 9-10 March 2023 <https://www.tut.ac.za/news-and-press/article?NID=716>
  
- (ii) Oscar Mokotedi, Brian Mantlana, Abel Ramoelo, Wongalethu Silwana and Philemon Tsele. *The water-Energy-Food nexus as the catalyst to enhance cooperative governance for climate change adaptation in South Africa*. The preliminary results of the project were presented at the launch of the COMPACT of Mayors and Administrators in Mpumalanga Province (09 – 10 December 2021).

## LIST OF ABBREVIATIONS

AEA.....	Albers Equal Area
4IR.....	Fourth Industrial Revolution
AUC.....	Area Under Curve
CDD.....	Consecutive Dry Days
CSIR.....	Council for Scientific and Industrial Research
CWD.....	Consecutive Wet Days
DALRRD....	Department of Agriculture, Land Reform and Rural Development (DALRRD)
DEM.....	Digital Elevation Model
DFFE.....	Department of Forestry Fisheries and the Environment
DOI.....	Digital Object Identifier
DSI.....	Department of Science and Innovation
ETCCDI	Expert Team on Climate Change Detection and Indicators
EFW.....	Energy-Water-Food
FEW.....	Food-Energy-Water
GCM.....	Global Climate Model
GDP.....	Gross Domestic Product
GeoTIFF.....	Geographic Tagged Image File Format
GGM.....	Geography, Geoinformatics and Meteorology
GHG.....	Greenhouse Gases
GLM.....	Generalized Linear Model
IDW.....	Inverse Distance Weighted
LULC.....	Land use and Land cover
MCP.....	Multiple Country Publications
NCCRD.....	National Climate Change Response Database
NetCDF.....	Network Common Data Form
NO.....	Number
NP.....	Number of Publications
PCC.....	Post-Classification Comparison
PY.....	Publication Year

ROC.....	Receiver operating Characteristic
SAEON.....	South African Environmental Observation Network
SANLC.....	South African National Land Cover
SCP.....	Single Country Publications
SDGs.....	Sustainable Development Goals
SRTM.....	Shuttle Radar Topography Mission
STATS SA.....	Statistics South Africa
TC.....	Total Citations
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
WEF.....	Water-Energy-Food
WF.....	Water-Food
WGS.....	World Geodetic System
WMO	World Meteorological Organization
WOS.....	Web of Science
WRC.....	Water Research Commission

## DEFINITION OF CONCEPTS

**Bibliometric analysis:** is a methodology that documents the publication patterns of authors. It uses statistical and mathematical methods to quantify the relationships and impacts of publications in a particular field of research

**Climate change adaptation:** is the process of adjusting to the current or expected future climate as a way to live in a changing environment.

**Geographic Information Systems:** is a set of computer applications that answer questions about location and relationships between objects using both spatial and attribute data. It performs a wide range of tasks, such as data creation, map creation, and relationship analysis.

**Geospatial tools:** is set of computer tools that allows to work with data that is geographical referenced (tied in a particular location). These include remote sensing, Geographic Information Systems (GIS), Global Positioning system (GPS) and internet mapping technologies.

**Land Cover:** refers to the surface cover of the earth, e.g., forests, grasslands, and water bodies. These provide a way to look at patterns and features in the landscape, which are crucial for understanding the extent, availability, and state of lands; the size, structure, and state of ecological systems; the potential for dispersal; and the effects of chemicals and other pollutants in and on the environment.

**Land use:** is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change, or maintain it. Land use activities include agricultural, residential, industrial, mining, and recreational uses.

**Logistic regression:** is a statistical technique that has been embraced by machine learning. It is employed to investigate an association between one dichotomous dependent variable and independent (continuous or categorical) variables. It is a member of the family of supervised machine learning models.

**National Climate Change Response Database:** serve as a resource for collecting and monitoring climate change interventions (mitigation and adaptation) on previous, ongoing, and upcoming initiatives to address climate change in South Africa through policies, plans, strategies, projects, and research.

**Nexus:** is a collection of important, context-specific interconnections between two or more natural resources that are used as inputs into systems that give humans access to necessities like food, energy, and water. It focuses on better integrated, cost-effective, and coordinated management and planning of natural resource use across sectors

**Post-classification comparison:** compares the areas and extent of Land Use and Land Cover classes between two periods with the purpose to determine changes in Land Use and Land Cover.

**Remote sensing:** is the practice of locating and monitoring the physical properties of an object by measuring its reflected and emitted radiation at a distance from the targeted object

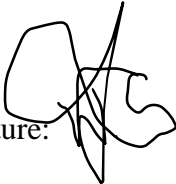
**Statistical machine learning:** is the process of creating models that can learn from data and make decisions or predictions by applying statistical approaches.

**Synergies:** describes an interaction between two or more objects when the total effect of the interactions is more than the sum of the individual effect.

**Trade-offs:** occurs when a greater quantity of a particular thing is required at the expense of less of another. It means that the activities cannot coexist.

## DECLARATION

I, Wongalethu Silwana declare that the dissertation, which I hereby submit for degree MSc Geoinformatics at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signature: 

Student number: 21756792

Month Year: December 2023

## **DEDICATION**

I dedicate my dissertation work to my mother, Thobeka Nosiyabonga Silwana for her unconditional love and support during my MSc research. A special dedication goes to my favourite person Owam George (O.G) whose been a great motivation in my life. I also dedicate this dissertation to my principal supervisor Prof. Abel Ramoelo whose been so good to me, without his support and guidance none of this work would have been possible.

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## CHAPTER 1                      GENERAL INTRODUCTION

### 1.1 BACKGROUND

There are signs already that climate change is increasing pressure on the cross sectoral water, energy and food resources (Scott, 2017; Pardoe *et al*, 2018). The best approach to manage the nexus of water, energy and food resources has come under scrutiny because of the mounting pressure from limitations of these natural resources. The nexus approach is a strategy that allows integrated problem solving by taking consideration of several factors concurrently (Liu *et al*, 2018). These interactions include synergies, where two components benefit from one another, and trade-offs, where progressing on a particular issue may require sacrificing on another (Breuer *et al*, 2019). The Water-Energy-Food (WEF) nexus is an effort to address challenges affecting WEF sectors by taking into consideration the inter-relatedness and interdependencies between these sectors to balance their perspectives and management (Hoolohan *et al*, 2018; Scott, 2017). It aims to enhance resource use efficiency and political cohesion by reducing resource trade-offs and increase synergies (Hoff, 2011). For example, it enables consideration of approaches for (i) addressing energy security without impacting further on food or water resources (ii) improving water security without increasing the energy burden in water management (iii) meeting rural job creation ambitions in a sluggish agricultural economy without overextending water and energy resources (Von Bormann and Gulati, 2014).

Future resource use management (such as global food systems, water management, and access to energy) will need to adapt in response to a growing global population, changing

climate and limited natural resources. In South Africa, where climate change is predicted to have particularly adverse impacts on water resources, arable land, and biodiversity, as well as primary industries, the risk of insecurity and the significance of interdependencies is likely to be intensified (Conway *et al*, 2015). The viability of natural resource-based sectors such as agriculture, forestry, fishing, tourism, and mining are likely to be affected. This in turn, will compromise efforts to address basic human needs, improve living standards and create employment. About 83% of the greenhouse gas (GHG) emissions in South Africa are generated by the energy sector (DEA, 2011). Climate change is mainly driven by these GHG emissions. South Africa faces climate change challenges, with average temperatures expected to rise by 6°C at the end of the century if GHG emissions are not reduced (Engelbrecht *et al*, 2015; Maúre *et al*, 2018).

Adapting to climate change is a critical policy problem for global society, and it requires support from the public and commercial sectors as well as government of all scales (Lim *et al*, 2005). Fortunately, the global response to climate change, which is led by the United Nations Framework Convention on Climate Change (UNFCCC), has prioritized adaptation as a critical response to climate change. The architecture to foster climate change adaptation at the global, regional, national and sub-national levels is rapidly expanding (Tompkins *et al*, 2010). For example, financial resources are proliferating to fund climate change adaptation activities (Ehrhart, 2022). There's advocacy of adaptation policies at different levels of government. Furthermore, there is an exponential growth in the literature on climate change adaptation that documents the consequences for ecological and social resilience at different geo-spatial scales (Nalau and verall, 2021; Wang *et al*, 2018).

South Africa has included adaptation as a critical component of its institutional framework on climate (GIZ, 2015). In recent years, adaptation has emerged as an important concept in climate and global change interventions, with water, energy, and food at the center of that public discourse (Madzwamuse, 2010; Fiske *et al*, 2014). Therefore, adaptation is closely related to attaining the sustainable use and management of water, energy, and food, which are vital to sustainable development (Rasul and Sharma, 2016). Successful adaptation requires multi-level collaboration through effective partnerships to prevent maladaptation

and achieve successful outcomes (Adger *et al*, 2005; Barnett and O'Neill, 2010). There is therefore a need to understand the role of the WEF nexus in adaptation with the aim of enabling the design, development and implementation of effective adaptation policies and strategies.

The challenges of sustaining the WEF nexus resources from the impacts of climate change are epitomized by the Mpumalanga Province, where highly productive agricultural land competes with coal mining for land and water use (Simpson *et al*, 2019). Approximately 61.3% of the Mpumalanga Province's surface area was subject to applications for prospecting and mining rights in 2014 (Solomons, 2016). Water security in the province of Mpumalanga is seriously impacted by both agricultural and mining land use activities (Ololade *et al*, 2017). This might be attributed to the sectoral planning in the government sectors that cater for important WEF nexus elements. That is, there is limited consideration or coordination of cross-sectoral interactions. As such, most government-led adaptation responses have a sectoral approach and are designed to meet sectoral goals (Mpandeli *et al*, 2018). The sectoral approach to climate change adaptation has not adequately addressed the question of whether observed adjustments reflect a societal shift towards well-adapting society or are unconnected actions (Conway *et al*, 2015; England *et al*, 2018; Nilsson *et al*, 2016). It is therefore 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 (Rasul and Sharma, 2015)

Taking Mpumalanga Province as the case study, this work recognizes that (i) availability of water, electricity (energy) and food (agriculture) are at the heart of national security and welfare, (ii) climate change poses a significant threat to these sectors (iii) precise and coherent data products need to be readily available for science and decision-makers and (iv) there is a need to address the gaps in the application of analytical methods to bridge the gaps in the ambitions of the water, energy and food sectors. As such, this study proposes to undertake a pragmatic approach that is based on geospatial analytical methods as a cooperative governance intervention to support WEF nexus climate change adaptation in South Africa's Mpumalanga Province.

Despite the wide recognition of the WEF nexus idea, there are difficulties in putting it into operation. The lack of accurate and consistent data is a major barrier to the practical implementation of the WEF nexus (Orimoloye, 2022). There is also a lack of analytical tools that provide evidence for policy and decision-making in WEF nexus (Caims and Krzywoszynska, 2016; McGrane *et al*, 2019). Furthermore, there is a limited application of transdisciplinary research approach that brings together scholars, practitioners, and society as collaborators of WEF nexus knowledge (Botai *et al*, 2021). Another major issue is the impact of climate change on the WEF nexus resources. As such, there are still significant questions to be answered, such as how climate change affects the WEF nexus and how it responds to the impacts of climate change. With the advent of the Fourth Industrial Revolution (4IR), assessment tools are needed to take stock of the impacts of climate change and implications of interventions at various scales.

The ability to collect, organize, analyse, retrieve, and visualize geographically referenced data and information useful for managing natural resources is provided by geospatial technology (Taguta, 2022). Integrating remote sensing with Geographic Information Systems (GIS) provides an effective way to analyse changes in Land Use Land Cover (LULC) (Halefom *et al*, 2018). Mapping of LULC provides a baseline assessment of WEF resources. Information about LULC is also required to allocate land suitable for different land use activities. This is important for minimizing competing land use interests between various organizations, communities, and users, as well as between the holders of customary rights and public authorities or private businesses. The study on the change of LULC patterns is important in addressing climate change and promoting sustainable development (Chang *et al*, 2018).

The United Nations is exploring and promoting the use of geospatial tools and data for monitoring and assisting with the implementation of the Sustainable Development Goals (SDGs), targets, and indicators (Holloway and Mengersen, 2018). The geospatial community plays an important role in efficient operation of national and municipal governments (Cooper, 1993). In essence, geospatial technology applied carefully ensures

sustainable planning and service delivery. When incorporated into sustainability strategies, GIS can transform decision-making processes and provide several advantages to both government and commercial organizations. These include the capacity to provide accurate and timely information as well as consistent monitoring and analysis to predict and illustrate potential future events (Johnson *et al*, 2008). Therefore, the use of geospatial approaches in WEF decision-making has the potential to be effective.

Unfortunately, the lack of relatively accurate and comprehensive geographical and demographic data, political considerations, and political barriers prevent many developing countries from effectively using geospatial data (Mennecke and West, 2001). There are challenges and restrictions associated with employing geospatial technologies beyond the academic realm, including data quality, privacy concerns, unpredictability, downloading, compatibility, processing, storage and visualization (Acharya and Lee, 2019). Fortunately, academic, and corporate researchers have worked hard to increase the value of geographic big data and leverage on it (Lee and Kang, 2015). The good news is that standardized techniques have been created in geographic information science and technology to evaluate, define, and spread quality attributes both quantitative and qualitative (Li *et al*, 2016). In addition, geographic science and technology has developed into a diverse area that today heavily relies on machine learning and signal processing algorithms to effectively handle the collected data and provide accurate outputs (Camps-Valls, 2009).

Beyond organizational data management producers, the Department of Forestry, Fisheries, and the Environment (DFFE), in collaboration with Statistics South Africa (Stats SA) and Department of Agriculture, Land Reform and Rural Development (DALRRD) (among others) in South Africa oversees the development of a governance framework for all public sector geospatial information that guarantees access to all users, encourages data sharing among data producers, and prevents the collection of duplicate data. Sharing current and real-time information is crucial, especially at the government level, to improve coordinated planning and cooperative governance amongst sectors. Therefore, there is an urgent need to enhance intergovernmental planning and coordination by the government departments. As

such, the current study stresses the need to improve cross-sector cooperation and coherence of efforts to properly tackle the WEF nexus-based adaptation challenges.

## 1.2 PROBLEM STATEMENT AND RATIONALE OF THE STUDY

The WEF sectors are all bound to experience numerous stresses resulting from climate change. The Mpumalanga Province, where agricultural production competes with coal mining for land and water consumption (Simpson *et al.*, 2019), is a prime example of the challenges involved in sustaining the WEF resources from the impacts of climate change. This situation has serious implications for adaptation strategies that are needed to ensure food, water, and energy security in the province. Mpumalanga Province is in Southern Africa, a region where the sectoral framework used for planning and development is analogous to the current approaches to climate change adaptation (Mpandeli *et al.*, 2018). This could lead to maladaptation since trade-offs are not taken into consideration. In a nutshell, cross-sectoral interactions are not sufficiently taken into consideration or coordinated. This happens even among the obviously interrelated climate-sensitive sectors such as water, energy, and agriculture. There is therefore a need to strengthen the WEF nexus perspective in public sector planning with the aim of improving the capacity to identify and incorporate sectoral interlinkages to the forefront of planning and decision-making (Rasul and Sharma, 2015).

A workable governance framework is required to allow the transition from a sectoral approach to a holistic approach. An end result could strengthen resilience to the negative impacts of climate change in WEF resources, leading to appropriate implementation of climate change adaptation strategies. The process should be informed by available national resources and constant communication with the research and civil society communities. The key to this information is having the data and information readily available to the decision-makers. Relevant data about WEF nexus are usually available, but it can be challenging to locate or access it (Voigt, 2015). This shows lack of communication between entities collecting data and decision-makers using those data.

Another problem in providing data in WEF nexus is lack of interoperability across different data products (Voigt, 2015). This is where decision support tools such as ‘geospatial technologies’ come into play. Geospatial techniques can help to address pressing issues in the WEF nexus by integrating data of various scales, resolutions and origins. For example, geographical information science and technology integrate spatial and non-spatial data to provide users with a better understanding of emergency situations and allow for more effective response. This shows that geospatial tools could be potentially used to ensure that the data services created for the WEF nexus and climate change adaptation meet the demands of decision makers and promote sustainability in this discourse.

Employing earth observation data and GIS approaches is needed for translating the WEF nexus into workable or relevant solutions in context with the impacts of climate change. This was highlighted by Dr. Aidan Senzanje, a senior lecturer from the University of Kwazulu-Natal, during a recent workshop organized by the Water Research Commission (WRC) and the Council for Scientific and Industrial Research (CSIR). The workshop was held at the CSIR’S International Convention Centre in Pretoria on 09 September 2022. This is because remote sensing provides useful information with spatial coverage that is useful for various WEF nexus analyses (Sanders and Masri, 2016). Therefore, a study employing earth observation data and geospatial techniques to synthesize and understand climate change adaptation through the lens of WEF nexus must be conducted in the Mpumalanga Province.

As such, this study sought to update climate change interventions or activities in DFFE's National Climate Change Response Database (NCCRD) as a main source for data provision that leads to simple access to coherent and complete data targeted at climate change adaptation and WEF nexus. This will promote the availability of precise and coherent data products for decision-makers and the scientific community. Such rigorous data-driven analytics techniques can help in accelerating the WEF nexus decision-making and thinking with the aim to reduce silo operation. The study will involve developing a model or framework for understanding the drivers of the location of the climate change adaptation interventions or actions spanning from environmental to socio-economic drivers. This model can be used to investigate options and trade-offs in decision-making processes to facilitate integrated resilience planning for WEF activities and climate change adaptation initiatives in the WEF nexus sectors. The study will produce outputs that are pragmatic and useful for

land resource management decisions. This study will be unique in that it will use socioeconomic, environmental, and climate change data to guide future project and programme planning by the public sector in Mpumalanga Province. Further, this study will contribute to novel approaches for implementing the WEF nexus at the provincial level in a practical, meaningful, and successful manner.

### 1.3 JUSTIFICATION OF THE STUDY

Several studies emphasized the need to ensure data provision and evidence-based analytical tools to improve decision-making in the WEF nexus and climate change adaptation. However, the drawbacks of the current WEF nexus analytical tools need an examination of other coherent and precise data products that would provide evidence for policy and decision-making. The current study seeks to bridge the data gap and lack of evidence-based analytical tools for decision-making that exist in WEF nexus and climate change adaptation, by exploring the capacities of GIS and remote sensing techniques in synthesizing and understanding climate change adaptation through the lens of WEF nexus.

### 1.4 STUDY AIM AND OBJECTIVES

The aim of this study was to propose a geospatial approach as a cooperative governance intervention to support Water-Energy-Food nexus climate change adaptation in South Africa's Mpumalanga Province. The objectives of the study were:

- to conduct a bibliometric review of and climate change adaptation review of Water-Energy-Food nexus and climate change adaptation.
- to evaluate the LULC changes that have occurred between 1990 and 2020 and their implications on Water-Energy-Food nexus resources in Mpumalanga Province.
- to determine if socioeconomic and environmental drivers could predict the location of WEF nexus based-climate change adaptation interventions.

---

## 1.5 RESEARCH QUESTIONS

- How can the use of geospatial tools, and which of those tools, could increase understanding and cooperative governance of the WEF nexus to better enable climate change adaptation in Mpumalanga Province?
- What is the extent and magnitude of LULC changes that have occurred in Mpumalanga Province between 1990 and 2020?
- Are there any implications of the LULC changes that took place between 1990 and 2020 on the WEF nexus resources in the study area?
- Which localities in Mpumalanga are hotspots for initiatives addressing climate change adaptation?
- Could the location of climate change adaptation interventions be explained by socioeconomic and environmental variables?
- Which parts of the Mpumalanga Province require adaptation projects or programmes to balance the WEF nexus trade-offs?

## 1.6 THE STUDY AREA

### 1.6.1 Background information and location of the Mpumalanga Province

The fundamental translation of the name Mpumalanga means "the place where the sun rises." It is in the northeast part of South Africa and is accounting for 6.5% (79490 km<sup>2</sup>) of South Africa's land surface area (Stats SA, 2011). The Mpumalanga Province is the second smallest province in South Africa and the country's fourth-largest economic contributor. The provincial headquarters are in Mbombela (previously known as Nelspruit). The province is bordered on the South by the Free State and KwaZulu-Natal, on the West by Gauteng, on the North by Limpopo and on the East by Eswatini and Mozambique (Eggink, 2015) (Figure 1.1). It is made up of 18 local municipalities and 3 district municipalities (Stats SA, 2016) (Table 1.1).

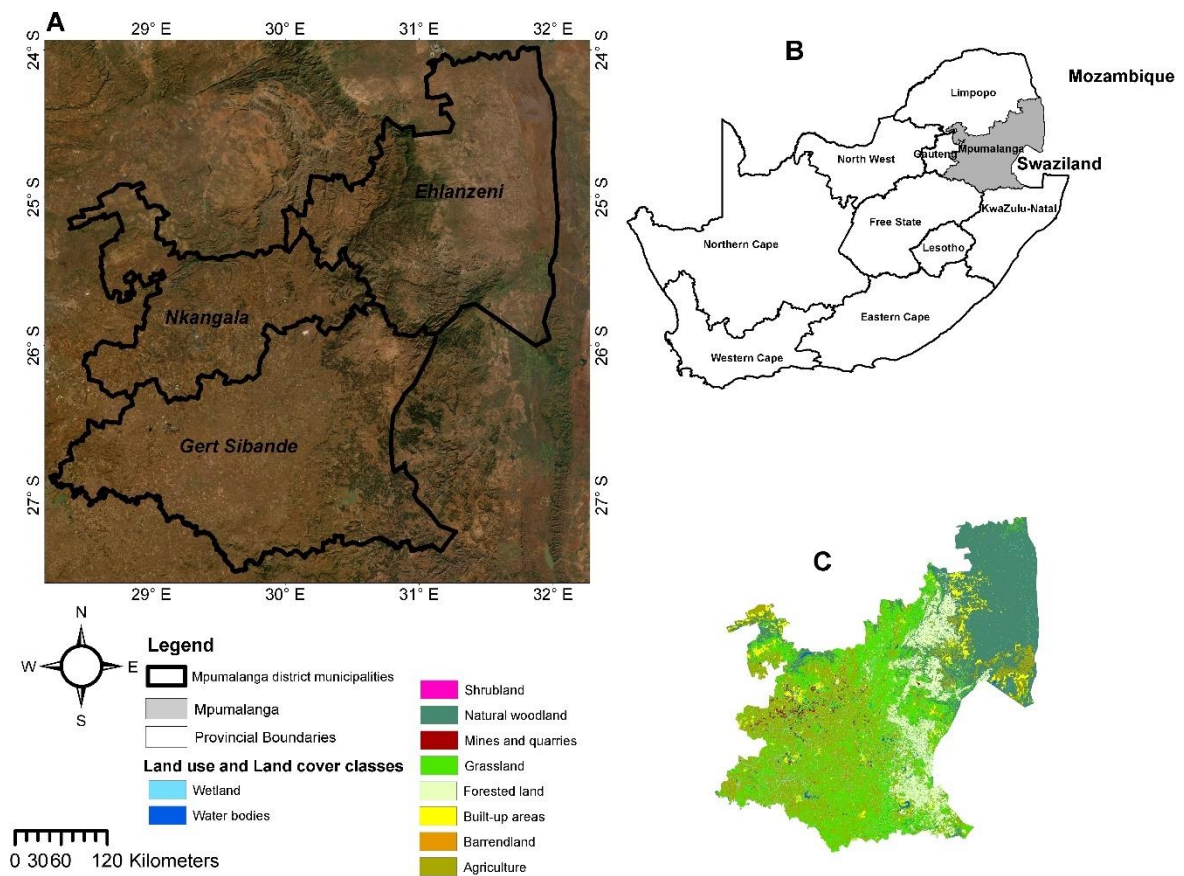


Figure 1.1: Location of the study area. (A) District municipal boundaries in Mpumalanga. (B) Mpumalanga Province relative to other provinces in South Africa. (C) Dominant LULC classes in Mpumalanga Province.

Table 1.1: District and local municipalities in the Mpumalanga Province.

District Municipalities	Ehlanzeni District	Nkangala District	Gert Sibande District
Local Municipalities	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

The province is well known for its distinctive and significant biodiversity. The two main dominant biomes found in Mpumalanga Province are grassland and savanna. 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). The grassland biome in Mpumalanga Province is essential for biodiversity but is also the least well protected, making it vulnerable to rapid modifications in land use (Figure 1.2).

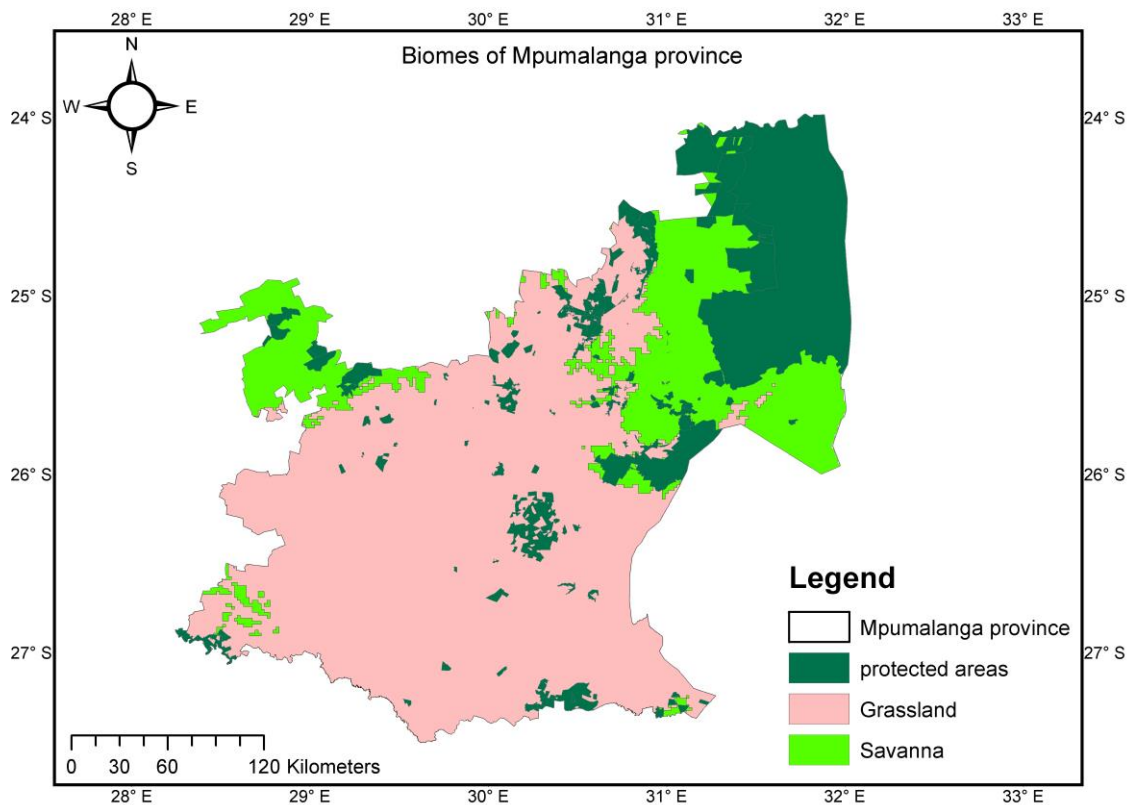


Figure 1.2: Biomes of Mpumalanga Province (SANParks, 2011). Current Biome delineations 2011 [Vector Geospatial dataset] Available from the Biodiversity GIS website (<http://bgis.sanbi.org/SpatialDataset/Detail/484>).

### 1.6.2 Topography of the study area

The Drakensberg escarpment divides the Mpumalanga Province in two, with the Westerly, high-altitude Highveld and the Easterly, low-altitude subtropical Lowveld (Celliers, 2019). The Highveld stretches for hundreds of kilometers eastwards until it reaches the escarpment in the north-east, where it plunges down to the Lowveld (Celliers, 2019). The topography of the province is made up of grasslands, plenty of valleys, mountain passes, rivers, waterfalls, wetlands and forests. Rivers and dams allow for the formation of landscapes like the Blyde River Canyon, the Kadishi Tufa waterfalls and Berlin Falls. The topographic features of the Mpumalanga Province are evident in Figure 1.3.

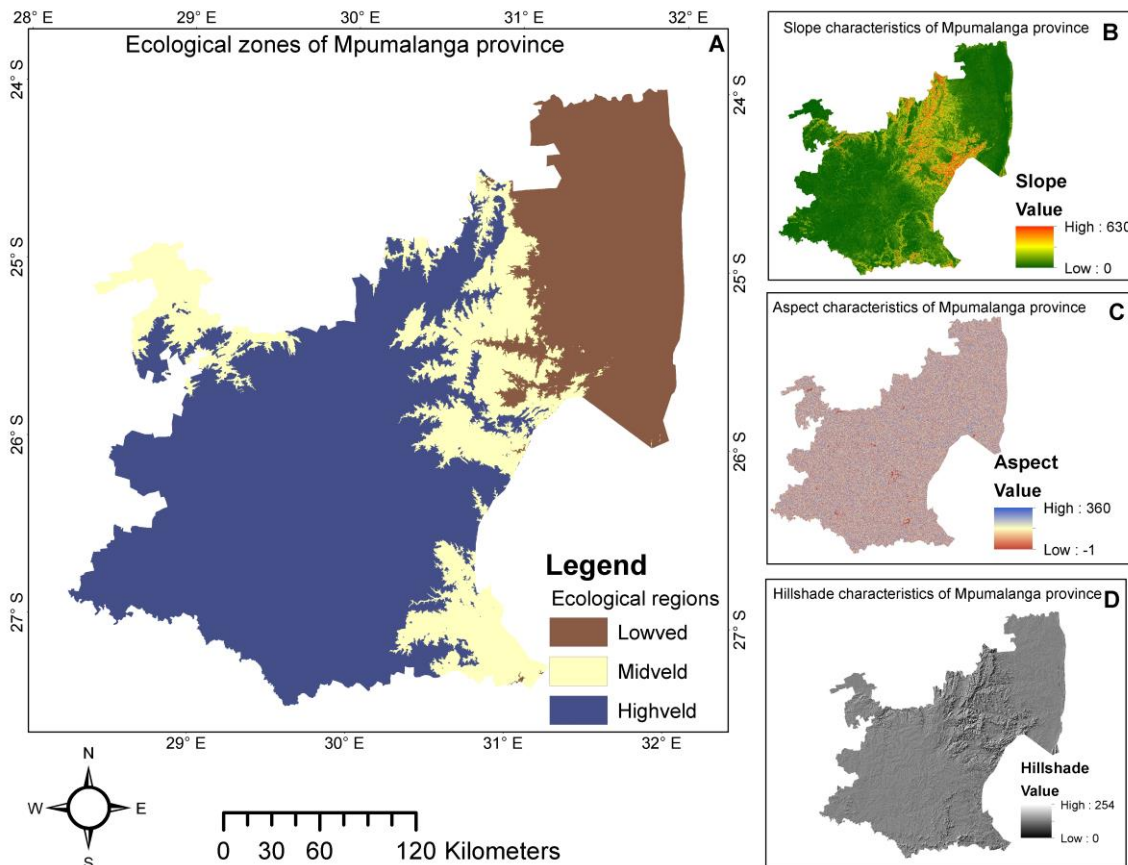


Figure 1.3: Topographic information of the study area derived from Shuttle Radar Topography Mission (SRTM)'s 30-meter resolution of digital elevation model. Available from the United States Geological Survey (usgs.gov) website <http://earthexplorer.usgs.gov/>. (A) Digital elevation Model (DEM) of Mpumalanga Province ecological zones, (B) slope, (C) aspect and (D) Hill shade.

### **1.6.3 The geology of the Mpumalanga Province**

The Mpumalanga escarpment, with its variety of geology and landforms, is one of the Great escarpments in South Africa (Viljoen, 2015). The Witwatersrand Supergroup (gold ore resources) and the Bushveld Complex (platinum group of minerals) are two of the most significant geological formations in the world, and both are in the province of Mpumalanga (Groenewald and Groenewald, 2014). The 1870 gold rush period can be seen in Barberton and Pilgrims Rest (Harrison, 2004), which has been declared a national monument. 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 province'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.

### **1.6.4 The water supply situation in the study area**

Groundwater, rainfall, and rivers are the primary sources of water supply in the study area. Water should be managed carefully because it is a rare resource in the province of Mpumalanga (COGTA, 2018). The Mpumalanga Province's water supplies are under pressure because of rising water demand brought on by an expanding population, together with increased agricultural and mining operations (MTPA, 2018; Wanda *et al*, 2017). The primary rivers are the Vaal, Olifants, Nkomati, Crocodile and Usuthu. The Inkomati-Usuthu, the Olifants, and the Vaal are the three Water Management Areas (WMA) that traverse provincial boundaries (WWF-SA, 2013) (Figure 1.4).

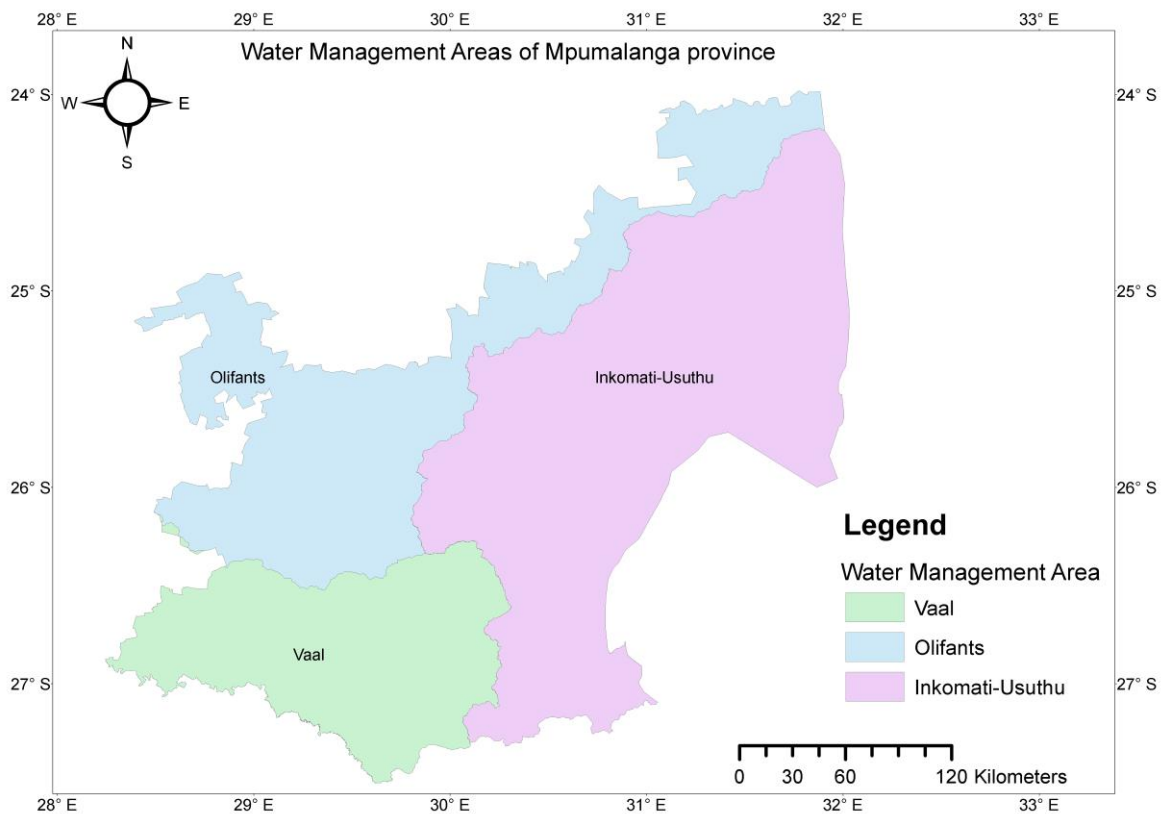


Figure 1.4: The water management areas in Mpumalanga Province (adapted from WWF-SA, 2013).

The Mpumalanga Province is home to a significant amount of South Africa's Strategic Water Source Areas (SWSAs), which make up to 50% of the country's average yearly run-off and occupy 8% of its territory (MTPA, 2014; Le Maitre *et al*, 2018). SWSAs are strategically located and play a significant role in supplying water to the province. Nevertheless, it has been noted that these SWSAs are at risk from large-scale plantations, coal mining, and land degradation (WWF-SA, 2013; Le Maitre *et al*, 2018). There are five SWSAs in Mpumalanga Province namely: (1) Mpumalanga Drakensberg water source area which supplies water to eMalahleni, Middleburg, Mbombela as well as Ba-Phalaborwa; (2) Mbabane Hills water source area which supplies water to Mbombela, Standerston, Ermelo, Swaziland and Mozambique; (3) Enkangala Drakensberg water source which supplies water to Mbalenhle, Standerston, Delmas, Volksrust and Ermelo; (4) Upper Vaal which is a critical water source area for downstream users and supplies water to few towns found in upper Vaal catchment including Ermelo; (5) Upper Usutu which supplies water required for Eskom's coal-fired

powered stations in the province of Mpumalanga (WWF-SA, 2013; Stats SA, 2023). Figure 1.5 shows SWSAs of Mpumalanga Province.

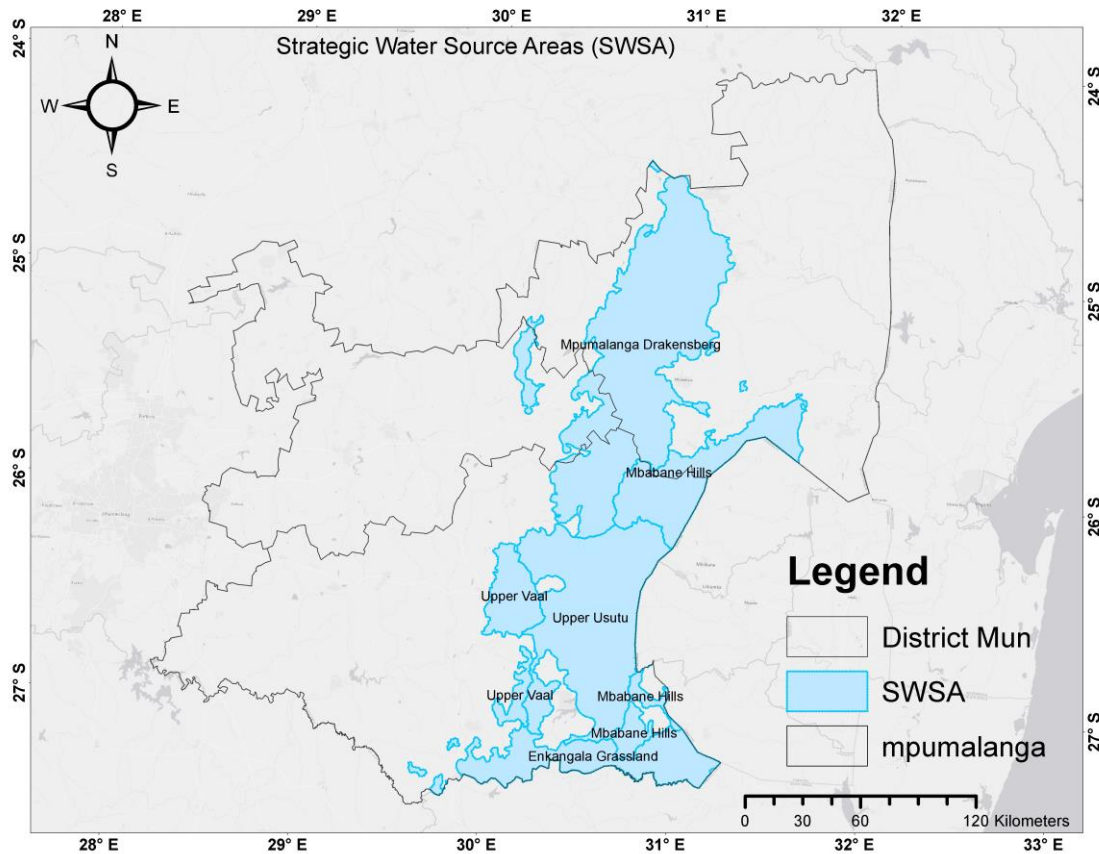


Figure 1.5: Strategic Water Source Areas of Mpumalanga Province. Source: South African National Biodiversity Institute. Strategic Water Source Areas [vector geospatial dataset] March 2021. Available from the Biodiversity GIS <http://bgis.sanbi.org/SpatialDataset/Detail/504>. SWSA= Strategic Water Source Areas, Mun= Municipalities.

### 1.6.5 Climate conditions in Mpumalanga Province

The study area has a varied climate. The Mpumalanga Province is in a section of South Africa where the bulk of rain falls during the summer (Adisa *et al*, 2018). The escarpment divides the area of summer rainfall into Lowveld and Highveld. The Lowveld has mild

winters and a subtropical climate, whereas the Highveld experiences freezing winters with little to no rain and hot, humid summers. Mpumalanga Province receives between 500 and 800mm of rain annually (Adisa *et al*, 2018). According to Kapwata (2015), humidity in Southern Africa is lowest in the winter and highest in the summer. Summer temperatures in Mpumalanga Province 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).

### 1.6.6 Livelihood

The natural resources of Mpumalanga Province 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 as 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 Province'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.

The Mpumalanga Province has poorly road and rail infrastructure, although they make it relatively accessible and promoting commercial and industrial development (Figure 1.6). The agricultural sector is critical in the battle against poverty and ensuring food security for Mpumalanga Province's 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).

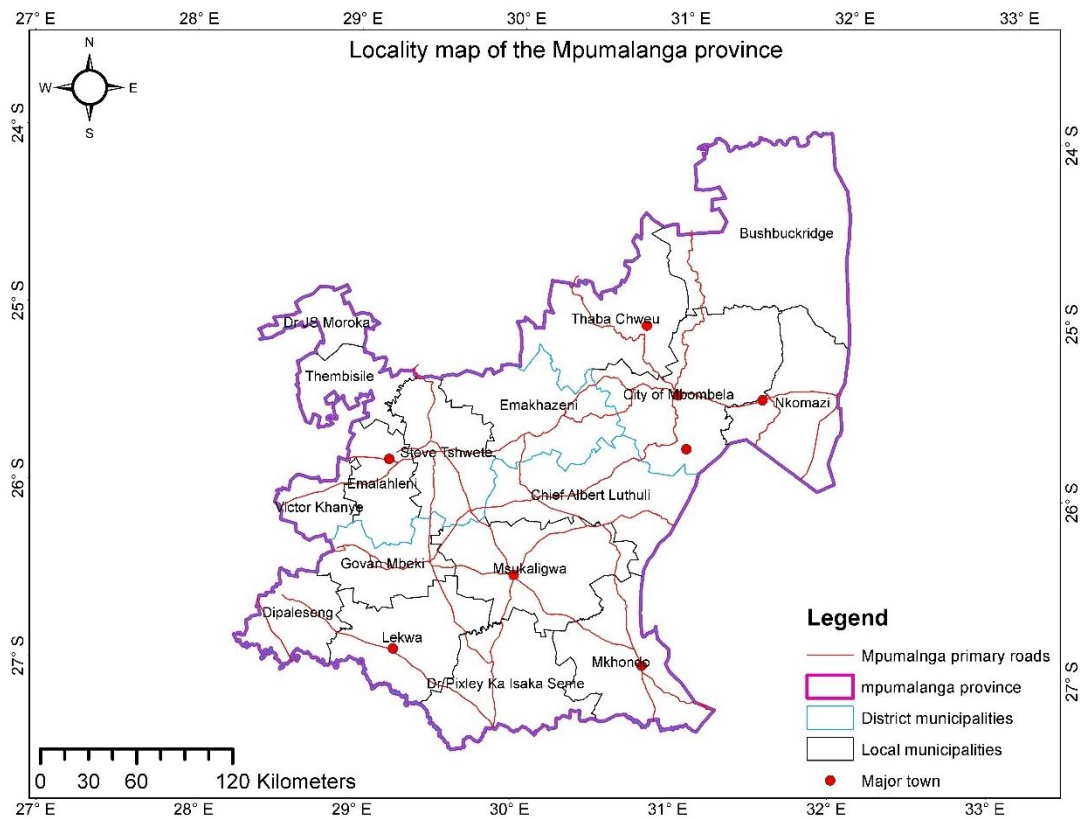


Figure 1.6: Locality map of the Mpumalanga Province.

## 1.7 ORGANISATION OF THE THESIS

The 5 chapters that make up this study are devoted to attaining the objectives of the study and responding to its research questions. Below is an overview of each chapter:

**Chapter 1** provides a comprehensive overview of the impacts of LULC changes and climate change on water, energy, and food as well as the efficacy of the WEF nexus approach for addressing complex challenges. The chapter also outlined the need for strategic development and an enabling framework for adaptation to ensure robust collective responses that minimizes trade-offs and maximizes synergies in the WEF nexus. The chapter went into detail regarding challenges encountered in the study area. The chapter also drew on the study's aim, objectives and research questions. Furthermore, a discussion on the study area's context of location, topographical features, geological features, biome types, supply of water, climate and livelihood was also presented in this chapter.

**Chapter 2** highlights relevant literature related to the current study, specifically, challenges and opportunities for implementing WEF nexus in South Africa, climate trends and WEF challenges and implications for climate change adaptation in Mpumalanga Province

**Chapter 3** presented a thorough analysis of the underlying intellectual trends in the research on WEF nexus and climate change adaptation. This chapter also discusses the data collection process, preparation, and methods used to evaluate communication, research practices, and citation patterns in WEF nexus and climate change adaptation research. The results of this chapter provide a scientific mapping of networks, trends, keywords, thematic analysis and content analysis. This chapter is addressing objective 1

**Chapter 4** focuses on remote sensing and GIS to detect LULC changes for the years 1990, 2014, 2018, and 2020. This chapter also provides a framework for classifying the LULC classes in the lens of WEF nexus. This chapter is addressing objective 2 of this study.

**Chapter 5** Locates the importance of understanding the role of WEF nexus in adaptation with the aim of enabling the design, development and implementation of effective adaptation policies and strategies. This chapter presented a framework that integrates the WEF nexus and climate change adaptation. This chapter is addressing objective 3 of this study.

**Chapter 6** wrapped up the research study. It presents a comprehensive overview of the findings from the study and a discussion how they may affect decisions about how to manage the resources in the face of climate change. The use of geospatial tools in the synthesis and understanding of climate change adaptation through the lens of the WEF nexus were explored, and their reliability was also assessed here. Finally, the chapter included suggestions for how to support WEF nexus as an adaptation approach.

## **CHAPTER 2                      LITERATURE REVIEW**

This chapter presents a short overview of the research on the challenges of achieving sustainability in the water-food and energy (WFE) nexus in the South African Province of Mpumalanga within the context competing land uses and climate dynamics. The chapter also discusses the key climatic trends and challenges that could compromise WEF resources. Further, challenges and opportunities for the implementation of the Water-Energy-Food nexus in South Africa has been explored.

### **2.1    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)

The Council for Scientific and Industrial Research (CSIR) and the Water Research Commission (WRC) convened a workshop on WEF nexus at CSIR'S International Convention Centre in Pretoria on 09 September 2022. The expected participants were leading researchers, government stakeholders (in water, energy and food sectors) and some

private sectors. However, it was noted that the invited speakers from the Energy and Food sectors were not present at the workshop. The workshop was aimed at strengthening the research-policy-practice interface for the WEF nexus in South Africa. During the Workshop, several experiences, and initiatives on translating the WEF nexus concept into policy were discussed with particular focus on progress, challenges and gaps in translating the WEF nexus into practical or applicable solutions for South Africa, in the context of the impacts of climate change.

Challenges and opportunities for the implementation of the WEF nexus in South Africa were presented and participants shared experiences on anchoring the WEF nexus in the current policy landscape of South Africa. The WRC has pledged to support the study on the WEF nexus and facilitate communication among academics, who are in turn tasked to turn academic outputs into a policy framework for WEF nexus. The workshop participants agreed on a series of suggestions, with some issues emerging as critical priority for consideration in future activities. These recommendations included focusing on human and institutional capacity development as well as transforming the WEF nexus idea into policy over the next 10 years. Furthermore, it was mentioned that more case studies are required in South Africa to draw in commercial and political leaders. As such, mine closure was identified as a key example of the application of WEF nexus in South Africa where 640 mines are deserted, and mining companies possess large areas of agricultural land. A WEF nexus can also be applied to irrigated agriculture, which uses larger portions of South Africa's water.

The Mpumalanga Province was also identified as a prime example of the challenges involved in sustaining the WEF nexus resources from the impacts of climate change, where agricultural operations compete with coal mining for land and water consumption (Simpson *et al*, 2019). More than 60% of the Mpumalanga Province's land surface area has been subject to applications for prospecting and mining licenses (Solomons, 2016). Studies show that the interest in coal mining that supports the country's energy demands is posing an increasing threat to food and water security (Davies, 2014; Ololade *et al*, 2017; Simpson *et al*, 2019). Both agricultural and mining expansion have a major adverse impact on the province of Mpumalanga's water security (Ololade *et al*, 2017). This could indicate the lack of cooperation in the government departments that manage important WEF nexus components.

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## 2.2 CHALLENGES AND OPPORTUNITIES FOR THE IMPLEMENTATION OF THE WATER-ENERGY-FOOD NEXUS IN SOUTH AFRICA.

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 increasing demand for and use of natural resources for development and their availability and quality are exacerbated by a decreasing state of the natural environment. If the effects of overexploitation and climate change are to be avoided, decision support systems, like WEF nexus, that are expressly driven by an extensive understanding of trade-offs, are required. The challenges impeding WEF nexus in South Africa from moving from theory to practice include a lack of awareness, institutional capacity issues, knowledge gaps, a lack of funding, and a lack of political determination to implement WEF nexus programmes and silo operations in the WEF space (Adom *et al*, 2022). Through policies and decision-making, a transition from theory to practice will give priority to social and economic development and human wellbeing (Botai *et al*, 2021). Additionally, for the science-policy-practice to accomplish this, more transdisciplinary paradigms for research capable of addressing complex nexus issues will be required.

Since there is very little evidence on the ground, many people continue to view WEF nexus as an academic exercise. This is attributed to the lack of analytical tools, data availability and decision support systems (Cairns and Krzywoszynska, 2016; Liu *et al*, 2017; Mpandeli *et al* 2018, Nhamo *et al*, 2018; TerraponPfaff *et al* 2018). This begs the question of how best to use information to effectively increase evidence-based policy and decision-making in WEF nexus. Boluwade (2021) states that the management of the WEF nexus can be effectively supported by observational datasets from satellite-based indicators. Remote sensing has become a reliable and consistent data source for solving societal issues, allowing for rigorous data-driven analytics techniques to better understand the WEF nexus (Pitts *et al*, 2020). In addition to the improvements in the sensing technology, the application results from the technology show high precision and accuracy (Jung and Pradhan, 2020). Making timely, well-informed choices requires the integration of information from several fields, including planning, decision-making, Geographical Information Systems (GIS) and Remote

Sensing (Hassan, 2015). Earth observation data and geospatial science are needed to develop a model that will provide better knowledge and solutions to synergically manage water, energy, and food in the face of climate change.

### 2.3 LITERATURE REVIEW OF CLIMATE TRENDS IN THE MPUMALANGA PROVINCE

The Mpumalanga province environment outlook report (2018/19) reveals that the province is currently experiencing changes in water supplies as a result of climate change. The province's important economic sectors such as mining, energy production, agriculture, and forestry are all threatened by water shortages. If warming continues at the current rate, this situation is expected to get worse, with temperatures projected to increase by 1.5°C between 2030 and 2052 (Allen *et al*, 2018). Extreme weather systems such as cyclones, heatwaves, flooding, and fires are occurring more often throughout the globe, which is reflecting the effects of climate change (Secretariat, 2018). The Mpumalanga province has also been impacted by past floods, droughts, fires, and storm events that have historically been prone to striking South Africa (SADEA, 2016). Notable disasters in the Mpumalanga province include storms, floods and droughts (DAEDLEA, 2015).

In Mpumalanga, the irregular variations in rainfall patterns and flood levels have become more frequent (DPWRT, 2015). Flooding can lead to water-borne illnesses that can be fatal (DARDLEA, 2015). Extreme weather occurrences in Mpumalanga not only have societal effects but also have an impact on conservation areas. For example, extreme flooding that occurred in the Kruger National Park between 2000 and 2012 removed at least 1.25 million tonnes of sediment from rivers and beds (Milan *et al*, 2018). Riparian forest that survived 2000 floods was removed by 2012 floods (Milan *et al*, 2018). Due to the significant rainfall in 2012, high dam levels and flooding issues were noticed (DWA, 2012). All three district municipalities were reportedly affected by the extreme floods that occurred in March 2014, which also resulted in damage to municipal infrastructure, provincial roads, bridges, and houses (NDMC, 2016). Cyclone Dineo impacted parts of the Mpumalanga province in February 2017 (NDMC, 2017).

Mpumalanga province was declared to be in a state of drought disaster management in the 2014/15 summer season (DAFF, 2016; NDMC, 2016). Nevertheless, according to the state of the environment outlook report (2018/19), the 2018 drought had the greatest impact on Bushbuckridge local municipality in the northeast of the province, which is in Ehlanzeni district municipality. Water supply and water quality are declining in the province of Mpumalanga, which is located in a water-stressed region. The province is categorized as having a medium risk of water scarcity (Think Hazard, 2019). According to Think Hazard (2019), the province of Mpumalanga has a high risk of wildfire occurrences.

#### 2.4 WATER, ENERGY AND FOOD NEXUS: CHALLENGES AND CLIMATE CHANGE ADAPTATION IN THE MPUMALANGA PROVINCE

Increasing Land Use Land Cover (LULC) changes and human development combined with climate variability are posing significant threats to water, energy and food security. If the consequences of overexploitation and climate change are to be avoided, land use planning must be integrated into adaptation strategies that are needed to ensure future water, energy, and food security. The traditional “silo” strategies failed because they were too linear for the current state of natural resource management, which calls for the use of natural resources with the least amount of regret, expressly guided by a clear knowledge of trade-offs (Wolde *et al*, 2021). To create adaptable ways of governance, new situations will call for new ideas and methods of thinking. Considering the increasing amount of evidence showing the impacts of climate change and the expanding population (Nhamo *et al*, 2018), a cross-sectoral strategy such as the WEF nexus is required to advance sustainable development.

This has led to promising results and improved communication between decision-makers and the scientific community. The WEF nexus achieves this by bringing together relevant stakeholders to address Sustainable Development Goals (SDGs) and facilitation of cooperative governance towards climate change adaptation planning. Even though WEF nexus has received uttermost attention from scholars, but demonstratable evidence which is hindered by lack of adequate data is slowing the translation of WEF nexus from research

into policy and practice. More integrated modeling, including web-based knowledge platforms, and new data, such as earth observational data, are needed to fully understand the important role that land and ecosystems play in understanding and supporting WEF decision making (Gomo *et al*, 2018).

In the context of Mpumalanga Province, the unregulated rampant spread of coal mining and its devastating impacts threatens the province's food and water security (Davies, 2014). This shows the lack of communication between relevant national government departments responsible for policies of these natural resources. As a result, there is fierce competition in the province for land and water use from coal mining and agriculture. 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.

Scholars will need to strive to create a practical governance framework that facilitates WEF nexus-adaptation initiatives. Geospatial methods and earth observation data may be used to identify consumption of resources hotspots and highlight priority areas for intervention. To move Mpumalanga Province closer to sustainable WEF nexus resource management, it is imperative to strengthen the WEF nexus approach in public sector planning. This can enhance the ability to recognize linkages across interdependent sectors and bring these interdependencies into the forefront of processes involved in planning and decision-making. A potential adaptation approach to address the challenges of resource management, poverty, hunger and inequality in the present and future is to concentrate on the trade-offs and synergies of the WEF nexus in a systematic way. Translation of the WEF nexus from research into policy and practice should therefore be factored into consideration for future research endeavours.

## 2.5 CONCLUSION

Thus, in this chapter key takeaways from main conclusions drawn from the scope of the workshop, which was organized by WRC and CSIR were summarized to form a contextual context for the analysis to be performed in the current study. An overview of the Challenges and opportunities for the implementation of the Water-Energy-Food nexus in South Africa has also been provided. The use of GIS tools and earth observation data to convert the WEF nexus into workable or relevant solutions in context with the consequences of climate change in South Africa has also been tackled in this chapter. The competing Land uses and climate dynamics prevailing in Mpumalanga Province, and the complexity of the associated decision-making processes in enabling adaptation, highlights a knowledge gap in the information needs and policy support required by stakeholders in the WEF sector. This shortfall has prompted the development of the current study.

**CHAPTER 3                    A BIBLIOMETRIC REVIEW OF WATER-  
ENERGY-FOOD NEXUS AND CLIMATE  
CHANGE ADAPTATION**

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### 3.1 ABSTRACT

Considering evidence of the impacts of climate change, as well as competing demands and limited resources, the Water-Energy-Food (WEF) nexus has emerged as an essential tool for promoting sustainable development. There is therefore a need to explore climate change adaptation through the WEF nexus approach. The main objective of this chapter was to map the underlying intellectual patterns of research on WEF nexus and climate change adaptation. This was achieved through bibliometric science mapping and content analysis. The data for the investigation, which spanned the years 2008 to 2020, was collected from Web of Science (WoS) and Scopus. There were 62 total results of documents obtained from the WoS and Scopus core collection databases, but only 47 were used for the analysis after 15 duplicates were removed. The scientific outputs of researchers, countries, institutions, journal sources, thematic evolution and collaboration networks were all examined using R package and aesthetically displayed in tables and graphs created in Microsoft excel and R studio. Visualization of similarities viewer (VOSviewer) was used to create the network visualization maps of all keywords co-occurrence. The results reveal that there has been an increase in scholarly literature on WEF nexus and climate change adaptation, reflecting the advent of studies addressing the issue of climate change and WEF nexus resources in the hopes of finding ways to guide policy development and governance structures in the face of climate change, population expansion, and inequality in terms of access to resources. It was observed that most scholarly literature interlinking WEF nexus and climate change adaptation is produced in Brazil, German, South Africa, United Kingdom (UK) and United States of America (USA). Research on climate change adaptation and WEF nexus has drawn uttermost attention to the keywords cluster that emphasises the need for strategic intent development and an enabling framework for adaptation to ensure robust collective responses that minimizes trade-offs and maximizes synergies in the WEF nexus. This study advances the discussion on the WEF nexus and climate change adaptation by showing current research practices and global contributions. This may support decision-makers in developing long-term strategic plans and setting up future research programmes in line with country's economic and political goals.

Keywords: water-energy-food nexus; climate change; adaptation; bibliometric analysis

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## 3.2 INTRODUCTION

A well-informed response is required to properly address climate change, which poses a serious threat to fulfilling the increasing demands for water, energy, and food. The impact will be increased because of the interconnections and interdependence that exist between these resources, collectively referred to as the Water-Energy-Food (WEF) nexus (Carter and Gulati, 2014). This presents opportunities for synergies and trade-offs. Synergies are created when two or more resources work together to produce a result that none of them could achieve on its own (Reijntjes *et al*, 1992), while trade-offs occur when the increase or efficiency of one resource is obtained at the expense of the quality or quantity of other resources (King *et al*, 2015). Achieving SDGs 6 (water), 7 (energy), and 2 (food) will need policies that appreciate the synergies between water, energy, and food while minimizing trade-offs (Fader, 2018). However, the vulnerability of these resources to climate change often leads to uncertainty over WEF security and poses difficulties for policymaking (Wu *et al*, 2022). Therefore, 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.

Climate change impacts and responses are generally cross-sectoral, which necessitates a coordinated approach within the three highly exposed sectors. The notion of the “WEF nexus” provides a useful framework for resolving complex challenges (Von Bormann and Gulat, 2014). Growing interest in exploring climate change adaptation through the WEF nexus approach has been driven by the accumulating evidence of climate change impacts. This is largely ascribed to the ability of WEF nexus to facilitate resource management and planning, which are necessary for climate change adaptation. Adaptation, therefore, has close links with achieving the sustainable use and management of water, energy, and food, which are vital for sustainable development. Adaptation achieves this by harmoniously addressing water, energy and food security challenges (Rasul and Sharma, 2016).

To assess the efforts made to understand the WEF nexus and climate change adaptation, this chapter examined the available literature. Analysing research performance enables

researchers to unpack the evolving intricacies of the subject of study, as well as hot topics and unmet needs (Sweileh, 2020). The current study employs bibliometric analysis to better understand the underlying intellectual patterns of research on WEF nexus and climate change adaptation. The Bibliometric analysis is the use of statistical and mathematical approaches to analyze published literature (Rapanovici, 2010). Bibliometric analysis is mostly used to measure the volume of scientific impact, institutions, countries and trend of a research on a specific field of study (Sweileh *et al*, 2016).

The main objective of this chapter was to map the underlying intellectual patterns of research on WEF nexus and climate change adaptation. This was achieved through scientific mapping of networks, trends, keywords, thematic analysis, and content analysis. Furthermore, the study evaluated the state of research for the WEF nexus and climate change adaptation in South Africa. Government decision-makers, politicians, or other interested parties can use this information to create long-term strategic plans, establish future research plans, and evaluate the performance of the current research of the country in the context of its economic and political objectives (Matcharashvili *et al*, 2014). Additionally, such investigations are necessary to understand the status of the country in terms of research quality and production in comparison to global and local standards (Matcharashvili *et al*, 2014).

### 3.3 MATERIALS AND METHODS

The main purpose of this section is to provide an overview of the data collection process, preparation and methods used to assess academic communication, research practices, and citation trends in WEF nexus and climate change adaptation research. Figure 3.1 provides a schematic flow chart diagram explaining the methodology followed in this study.

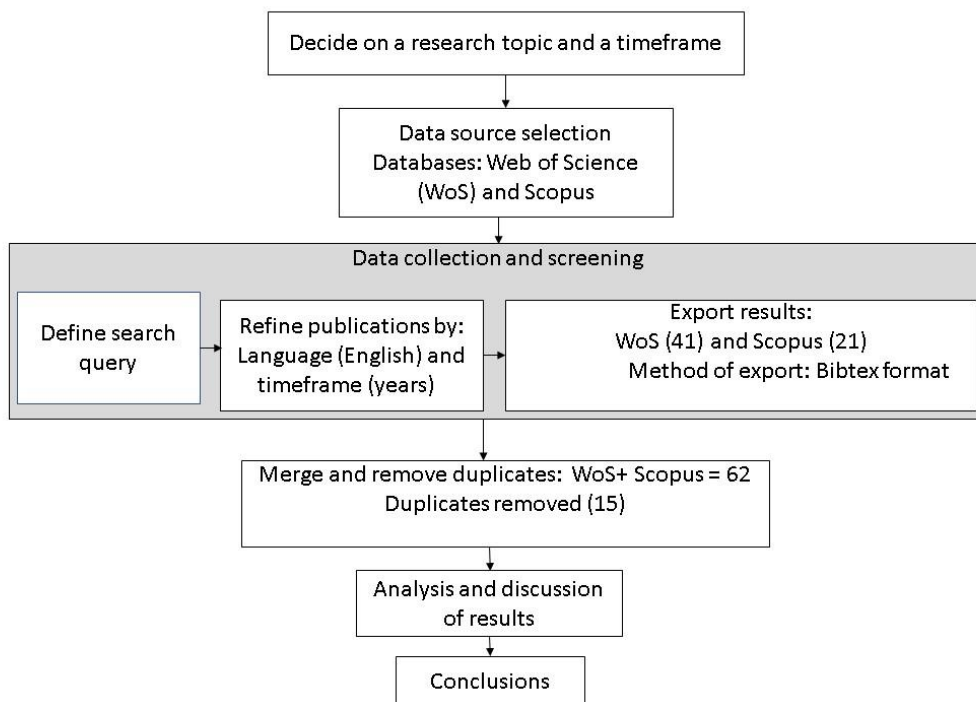


Figure 3.1: Methodological framework of bibliometric analysis

### 3.3.1 Database

In every bibliometric investigation, the first step is to choose the proper database to search for relevant documents. Most scholars acquire published literature for bibliometric analysis from the Web of Science (WoS) and Scopus databases (AlRyalat *et al*, 2019; Pradhan and Zala, 2021). Scopus and WoS are regarded as reliable sources for bibliometric research since they have the largest collection of abstracts and citations of peer reviewed scientific articles, books, and conference proceedings (Salisbury, 2009). They also cover a wide range of scientific fields, including science, anthropology, social sciences, and technology. Owing to the difficulties of manually merging the two databases due to dissimilar tag fields, researchers conduct bibliometric analysis on each database separately (Echchakoui, 2020). A few researchers often use two databases to do a single integrated analysis, but do not disclose how they achieved it, as this could lead to ineffective results if the merging method is unsuitable (Ertz and Leblanc-Proulx, 2019). Therefore, the question of which database to use in a bibliometric investigation has become increasingly important.

WoS was previously the sole available database for bibliometric analysis, but Scopus has emerged as a serious competitor since its launch by Elsevier (Pranckuté, 2021). The current investigation started by examining the benefits or singularities of WoS and Scopus. WoS was the first global bibliographic database, and it quickly rose to the top of the list for bibliometric assessments, research evaluation, and journal selection (Li *et al*, 2018). It is used for thoroughly data-intensive investigations and scholarly library research across many academic disciplines (Li *et al*, 2018). Zyoud *et al* (2017) indicated that WoS includes the most reliable and high-impact scientific studies.

Scopus on other hand, is a database that indexes a greater number of publications than PubMed, google scholar and web of science (Falagas *et al*, 2008), making it an ideal resource for doing bibliometric studies. Scopus is a curated database, meaning that the information it contains has been carefully selected for inclusion (Baas *et al*, 2020). Scopus data has been used as a source for bibliometric studies, showing its capabilities for various types of analyses (Nduku *et al*, 2021; Özcan and Batur, 2021; Sweileh, 2020; Romero and Portillo, 2019). Scopus is simple to use and offers an interdisciplinary feature that allows researchers to search outside their field (Burnham, 2006).

Many studies show that both databases are excellent resources for bibliometric investigations (Zhu and Liu, 2020). Sánchez *et al* (2017) acknowledged that Comparing WoS with Scopus in terms of performing bibliometric analysis does not imply that one is better than the other. Mongeon and Paul-Huns (2016) and Fernández *et al* (2010) concur that Scopus and WoS work well together. Hence it is imperative to use both databases as they complement each other. For that reason, the current study conducted a bibliometric analysis of available literature on the WEF nexus and climate change adaptation research using both Scopus and WoS databases.

### 3.3.2 Searching strategy

The most important step when preparing for a bibliometric analysis is to define the subject or problem to be investigated. A good bibliometric review will be focused on published evidence and have a clear focal point. Relevant literature is generated through Search terms

or keywords that are subject-specific or topic specific. However, Mejia *et al* (2021) noted that it is difficult to create a proper search query that will return as many documents as possible while excluding unnecessary information. It is also difficult to build a search query for topics with little history and no defined ontologies, without losing the overall number of relevant documents. The aim of the study was to map the intellectual structure of the WEF nexus and climate change adaptation. Since this is still a relatively new idea, the study conducted a thorough analysis to generate potential search terms. Researchers are still struggling to define WEF nexus. For example, energy experts, hydrologists, and agronomists use the phrases “energy-water-food nexus,” “water-energy-food nexus,” and “food-energy-water nexus,” of which they are all referring to the same phenomenon. Adding climate change adaptation, a concept that scholars continue to struggle to understand makes it much more challenging.

However, the current study created a subject-specific and thorough search query to find all relevant literature on WEF nexus and climate change adaptation related subject matter. The search terms "Water-Energy-Food nexus" AND "climate change" AND "adaptation" OR "Energy-Water-Food nexus" AND "climate change" AND "adaptation" OR "Food-Energy-Water nexus" AND "climate change" AND "adaptation" were used to find all publications related to the WEF nexus and climate change adaptation on both WoS and Scopus databases. The Boolean operator "AND" combined the search terms to find publications with all combined search phrases, while “OR” found publications that contained any of the combined search terms. The search query was based on document title, abstract and keywords. Since the WEF nexus concept was developed in 2008 (Wiegleb and Bruns, 2018), documents from the 2008 to 2020-time range were searched. The search query was generated on the 06<sup>th</sup> May 2021.

### 3.3.3 Preparation

The search query returned 41 and 21 document results from WoS and Scopus, respectively. All document types were considered for the current investigation including those with less stringent review process, since they can provide important concepts and frameworks. De Oliveira *et al* (2019) asserted that only documents published in English should be chosen for

bibliometric studies. Therefore, the search only returned publications that were authored in English and related to the WEF nexus and climate change adaptation. The bibtex format was used to export all generated results from both databases. The exported bibtex data included citation information, bibliographical information, abstract and keywords, funding details among other information.

Retrieved documents were store in a folder called “databases”. Data quality is often a challenge in bibliometric research since manually cleaning and disambiguating data takes a long time (van den Besselaar and Sandström, 2016). Van den Besselaar and Sandström (2016) further detailed that the current methods for data cleaning are far from flawless or even ideal. Linnenluecke *et al* (2020) cautioned that if duplicates are not deleted, publications may come out larger than the real number resulting in erroneous analysis. Gurney *et al* (2012) agreed and asserted that automated methods are needed to identify patterns of similarity. The current study prepared all files for data cleaning and duplication detection before interpreting the results.

R studio was used in this work to merge and remove duplicate data from the two separate databases (WoS and Scopus). R studio is an integrated development environment for the r programming language (see: <https://www.rstudio.com/products/rstudio/download/#download>, accessed on the 08<sup>th</sup> September 2021). The first step in cleaning bibliometric data on R studio is to install a bibliometrix package which provides a set of quantitative research in bibliometric and scientometrics. All the information that was acquired from the databases was saved in the working directory and it was given a name “databases.”. The script `<library(“bibliometrix”) >` was executed to import bibliometrix library and the function `<getwd()>` was executed in the command-line interface (CLI) to navigate to the working directory folder. As shown in appendix (A.1.1), the imported bibtex files were assigned names such as “My1” for WoS and “My2” for Scopus. The `convert2df` function was used to convert the bibtex files into data frame. The `mergeDbsources` function was executed to combine the two databases. This function also identifies and delete the duplicated documents in the bibliometric data frame (A.1.1). After merging and deleting duplicate documents, the total number of documents was 47, which was then uploaded to biblioshiny and Visualization of similarities viewer (VOSviewer) for bibliometric mapping and analysis. The cleaned-up file was given the name “My”.

### 3.3.4 Data analysis

This section describes the analytical and visualization tools used in the current study to evaluate and analyse publication numbers, citations, prolific authors, top journals, network collaborations, keywords co-occurrence, thematic progression of research and most productive countries and institutions. The bibliometric science mapping and content analysis was done in line with past literature analytical techniques (Nduku *et al*, 2021; Salam *et al*, 2021). The scientific outputs of researchers, countries, institutions, journal sources, thematic evolution and collaboration networks were all examined in biblioshiny and aesthetically displayed in tables, maps and graphs created in Microsoft excel and R studio.

Visualization of similarities viewer (VOSviewer) version 1.6.18.0 (available from <http://www.vosviewer.com/>) was used to create the network visualization maps of all keywords co-occurrence. VOSviewer is a free software tool developed by Nees Jan Van Eck and Ludo Walton of Leiden University's Centre for Science and Technology Studies (CWTS). It is open to the bibliometric community for free. This tool extracts bibliographic networks from bibliographic data, such as co-authorship, co-occurrence, and citation-based networks (Moral-Muñoz *et al*, 2020). The minimum number of occurrences of a keyword was set to 4. There was a total of 393 keywords in 47 publications, but only 25 of them met the criteria. Furthermore, all the unnecessary information and keyword synonyms were thoroughly evaluated and changed or removed. This resulted into 22 keywords for further analysis. With the use of the keywords plus field, this research also produced a visual representation of the major concepts in the body of knowledge of this research field.

## 3.4 RESULTS AND DISCUSSION

A wide range of publications were used for further investigation, including book chapters, proceeding papers, articles, and reviews (Table 3.1). The key information about the data used

for the study was retrieved from biblioshiny. Biblioshiny is a web-based application that allows non-coders to use bibliometrix package.

Table 3.1: Most important details regarding the data retrieved.

Description	Results
<b>MAIN INFORMATION ABOUT DATA</b>	
Timespan	2013:2020
Sources (Journals, Books, etc)	38
Documents	47
Annual Growth Rate %	47.24
Document Average Age	4.6
Average citations per doc	34.45
References	465
<b>DOCUMENT CONTENTS</b>	
Keywords Plus (ID)	226
Author's Keywords (DE)	179
<b>AUTHORS</b>	
Authors	194
Authors of single-authored docs	3
<b>AUTHORS COLLABORATION</b>	
Single-authored docs	3
Co-Authors per Doc	4.91
International co-authorships %	40.43
<b>DOCUMENT TYPES</b>	
article	29
article; book chapter	1
book chapter	3
proceedings paper	3
review	11

### 3.4.1 Research growth of publications on WEF nexus and climate change adaptation

The WEF nexus was developed in the late 2000s and early 2010s as the way to sustainably manage water, energy, and food (Mabhaudhi, 2018). It became well-known following the Bonn 2011 nexus Conference because of the most influential background paper, “Understanding the nexus: Background paper for the Bonn2011 nexus Conference,” which was published in 2011 (Hoff, 2011). Researchers began to think about the WEF nexus in the context of adaptation, since climate change is expected to cause multiple stresses on the sectors of water, energy, and food (Rasul and Sharm, 2016). However, research interlinking WEF nexus with climate change adaptation is still in early stages. This is expected since WEF nexus is still a developing notion (Allouch *et al*, 2015; Pandey and Shrestha, 2017). The results based on the data that was collected from Scopus and WoS on 06 May 2021 show that the first publications interlinking the WEF nexus with climate change adaptation emerged in 2013.

Figure 3.2 shows the annual growth in publications on the WEF nexus and climate change adaptation subject from 2013 to 2020. The results reveal that there has been an increase in scholarly literature on this emerging discourse, with an annual growth rate of 47.24% (Table 3.1). The long-term growing trend, however, witnessed a sharp drop in 2014 before seeing unexpected rebound in 2015. The overall publication trend linked to the WEF nexus and climate change adaptation indicates that the year with the highest research production was 2020, with 15 publications, followed by 12 publications in 2019. When looking at the number of publications relating to the WEF nexus and climate change adaptation subject from 2013 to 2020, it becomes evident that the number of publications interlinking these concepts increased significantly, reflecting the advent of studies addressing the issue of climate change and WEF nexus resources in the hopes of finding ways to guide policy development and governance structures in the face of climate change, population expansion, and inequality in terms of access to resources. In each of the years 2018, 2019 and 2020 more than 10 articles were published in this subject matter. This shows that this trend will continue to grow at a rapid pace, indicating the worldwide significance of the WEF nexus Approach in tackling climate change challenges.

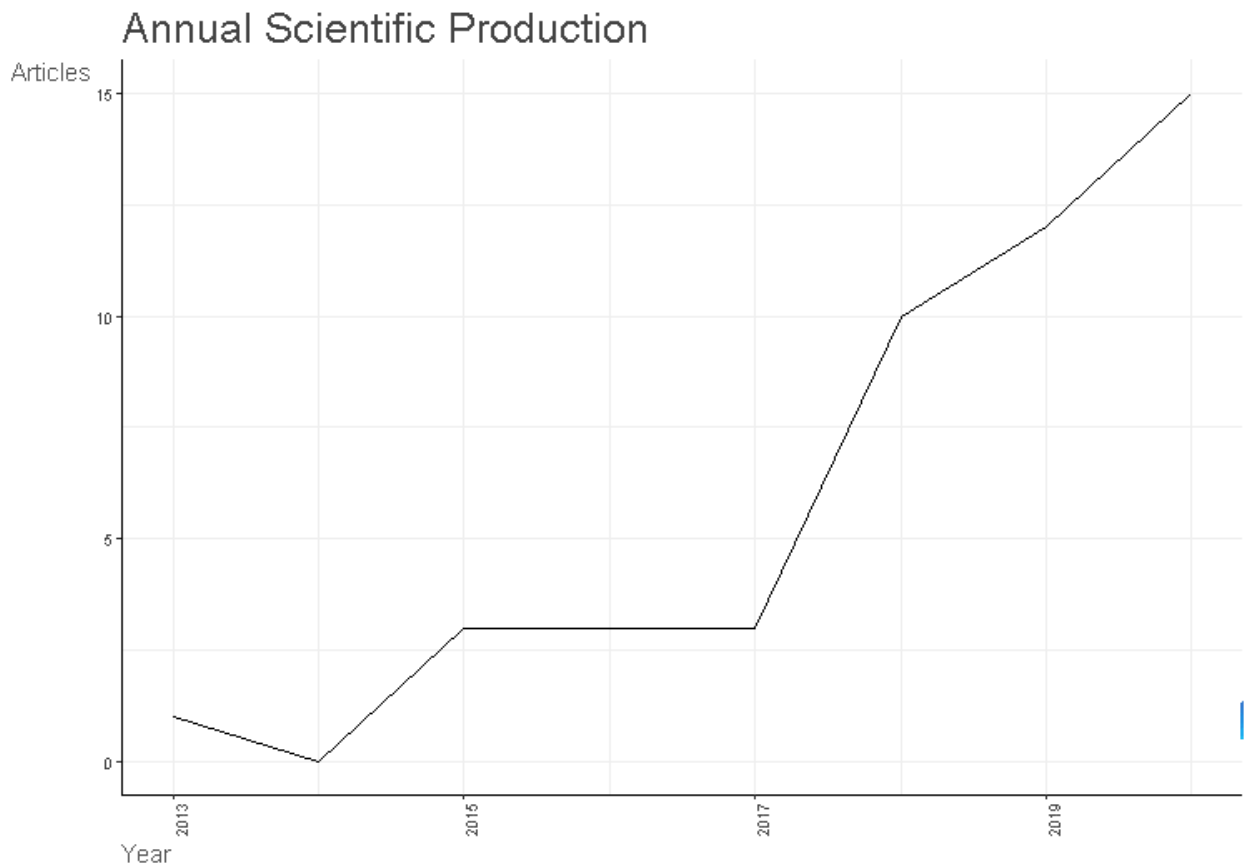


Figure 3.2: Annual growth of publication in WEF nexus-related literature (2013 – 2021)

The publications relating to the WEF nexus and climate change adaptation generated the most citations, with an average of 15.75 in 2016, and 10.15 in 2015 (Figure 3.3). The lowest average citation was 3.59 in 2019 and 3.91 in 2013. The average citation trend was not consistent during the research period.

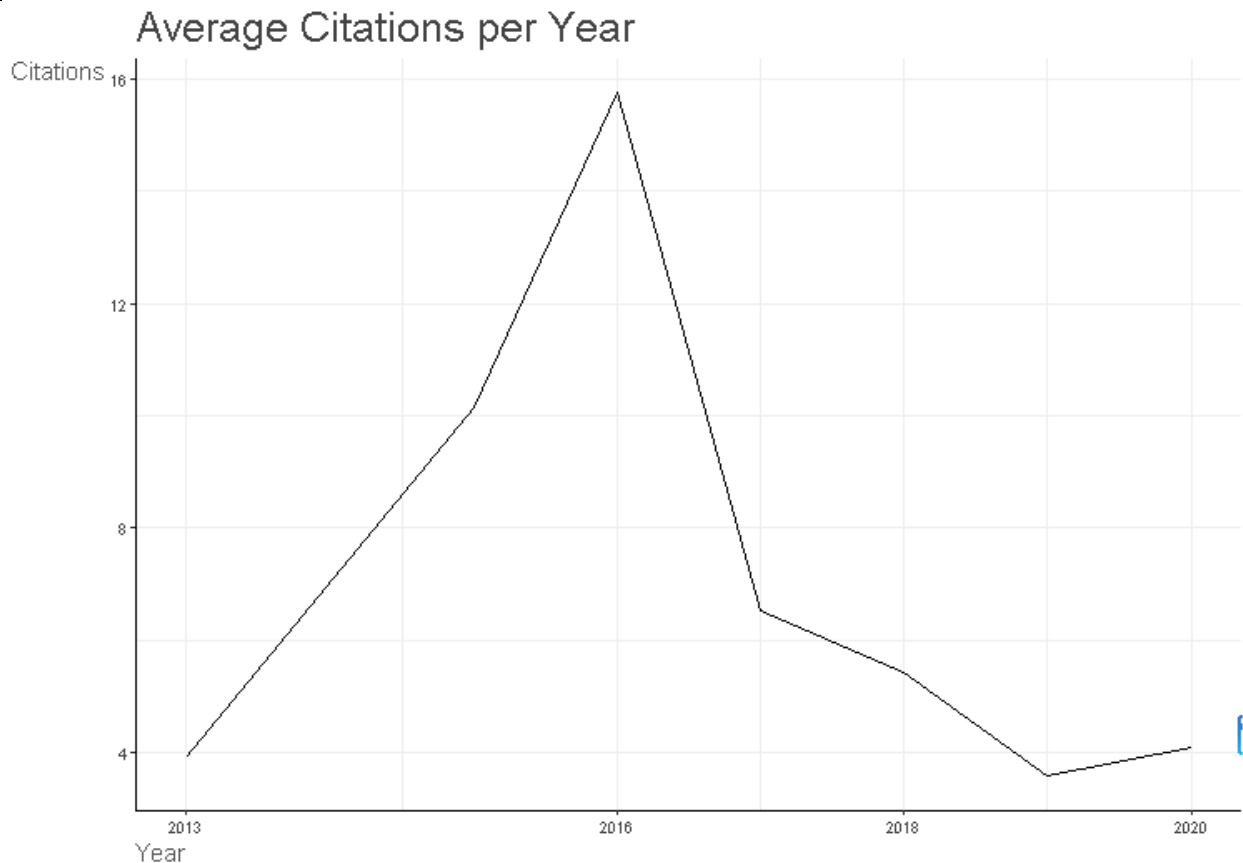


Figure 3.3: Average citations per year

### 3.4.2 Most prolific researchers in the subject of WEF nexus and climate change adaptation

A total of 194 authors from 19 countries and 131 different institutions published 47 documents on the notion of WEF nexus and climate change adaptation between 2013 and 2020. There are only 3 single-authored documents (Table 3.1). The results suggest that collaboration is important for authors researching on WEF nexus and climate change adaptation. The average number of co-authors per document is 4.91 and international co-authorships is 40.43%. Productivity and impact are the two primary factors to consider when assessing an author's relevance in a certain field (Forliano *et al*, 2021). Figure 3.4 uses both factors to provide an overview of the most prolific authors in the subject of WEF nexus and climate change adaptation.

The number of publications written by an author in a certain period was used to assess productivity of the author, while the number of citations obtained each year was used to assess the impact of the author. The results shows that Nhamo has the highest number of publications (4 in total) and the highest h-index (4 in total), which suggest that Nhamo is the most productive author in this research field. H-index is helpful when comparing the impact and production between researchers, since it equally weighs the quantity of publications produced and the number of citations to those publications (Hirsch and Buela-Casal, 2014). The results also show that Nhamo started publishing in this subject in 2018 with total citations per year of 10.17. On other side, Table 3.2 shows that Conway earned the highest citation counts of 385, which suggest that Conway has the highest local impact in this subject matter. Figure 3.4 shows that Conway is one of the pioneers in this area of study, publishing the first paper on it in 2015 and receiving an average citation of 29.23 per year. Conway’s work helped other academics to start seeing the WEF nexus in the context of climate change adaptation. Other researchers and their scientific outputs are also included in Figure 3.4 and Table 3.2.

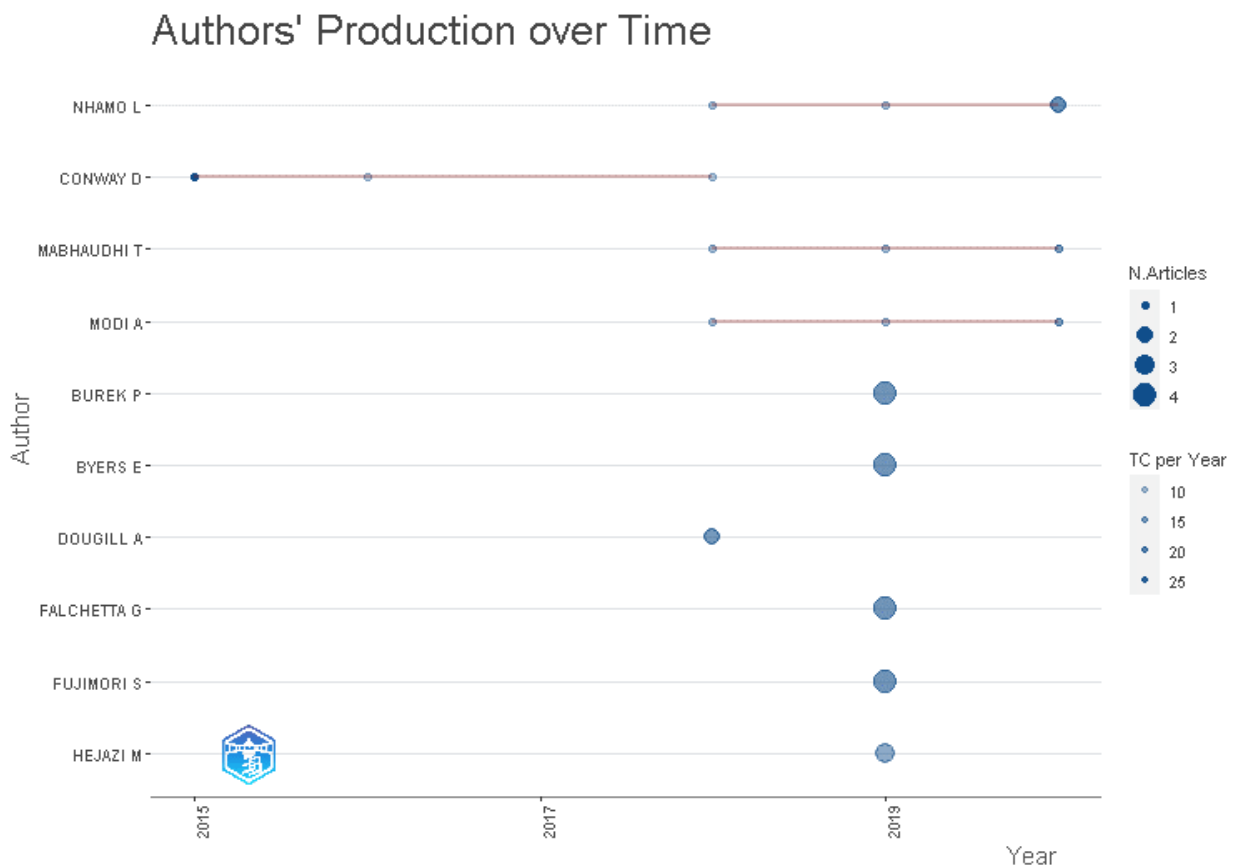


Figure 3.4: The top 10 author’s production over time. *The timeline for the author is shown*

by the line; the size of the bubbles reflects how many papers an author produces each year; the bubble's strength of colour relates to the overall number of citations each year; The first bubble on the line indicates the first publication the author made in the subject; The number of articles each author publishes each year increases with the size of the bubble. Higher citation counts are shown by bubbles with stronger colour intensity.

Table 3.2: The top 10 most locally cited authors ordered by the total number of citations (highest to smallest)

Element	h_index	g_index	TC	NP	PY_start
CONWAY D	3	3	385	3	2015
RASUL G	1	1	284	1	2016
SHARMA B	1	1	284	1	2016
DALIN C	1	1	264	1	2015
DERYNG S	1	1	264	1	2015
KRUEGER T	1	1	264	1	2015
LANDMAN W	1	1	264	1	2015
LANKFORD B	1	1	264	1	2015
LEBEK K	1	1	264	1	2015
OSBORN T	1	1	264	1	2015

TC= Total Citations; PY= Publication Year; NP= Number of publications

### 3.4.3 The most contributing sources and documents in the subject of WEF nexus and climate change adaptation

Bibliometric study can assist authors in choosing the best journal to submit their research for publication (Kalantari *et al*, 2017). The results of the top 10 most relevant sources in the subject of WEF nexus and climate change adaptation are shown in Figure 3.5. The results reveal that the climate policy, and environmental sciences & policy are at the top of the list, each with 3 publications. Other relevant sources include International Journal of Environmental Research, Journal of Cleaner Production, Science of the Total Environment, Sustainability and Water. For further analysis the local citation was used to assess the

relevance of the source within the examined collections (Aria and Cuccurullo, 2020). Table 3.3 reveals that climate policy generated the highest number of local citations, with 3 articles and 383 total citations. Table 3.3 also shows that climate policy started publishing in this subject matter in 2016. The second most locally cited source is nature climate change, which started to publish on this subject matter in 2015. It's remarkable to notice that the nature climate change source has just a single publication in this subject matter with 264 citations total. Surprisingly, the top 10 most locally cited publications based on the data analysis did not include some of the sources that were among the top 10 most relevant sources, such as sustainability, water, 2019 IEE African, aims geosciences, and an introduction to the circular economy.

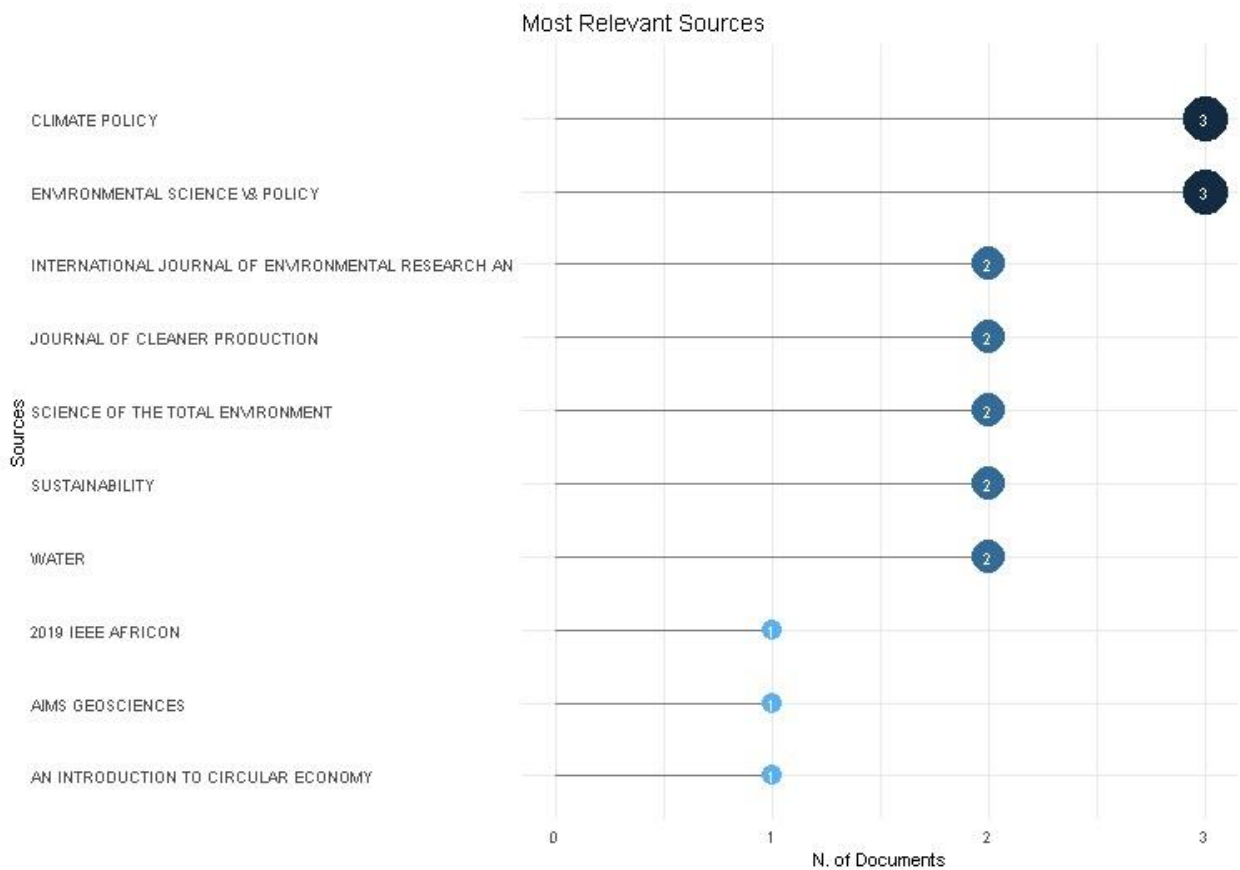


Figure 3.5: The top 10 most relevant sources.

Table 3.3: The top 10 most locally cited sources ordered by the total number of citations

(highest to smallest)

Element	h_index	TC	NP	PY_start
CLIMATE POLICY	3	383	3	2016
NATURE CLIMATE CHANGE	1	264	1	2015
ENVIRONMENTAL SCIENCE \& POLICY	3	133	3	2013
INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH	2	113	2	2018
CLIMATE RISK MANAGEMENT	1	66	1	2016
ENVIRONMENTAL RESEARCH LETTERS	1	66	1	2017
URBAN CLIMATE	1	65	1	2017
SCIENCE OF THE TOTAL ENVIRONMENT	2	64	2	2019
CURRENT OPINION IN ENVIRONMENTAL SUSTAINABILITY	1	61	1	2018
RENEWABLE \& SUSTAINABLE ENERGY REVIEWS	1	46	1	2018

*TC= Total citations, NP= Number of Publications, PY= Publication Year*

This study further examined the global citation of publications to analyse the most influential documents in the subject of the WEF nexus and climate change adaptation. The content of highly cited publications is incredibly helpful for spotting trends and assessing the effectiveness of research in each field of study (Wohlin, 2007). Global citation measures the number of citations a document has received from all sources and its impact, which may be larger from other disciplines (Agbo *et al*, 2021). Global citations focus on the impact at the global scale. Table 3.4 lists the top 10 documents in the dataset that have the greatest impact on the topic of the WEF nexus and climate change adaptation.

The results show that Rasul and Sharma (2016)'s paper titled "The nexus approach to water–energy–food security: an option for adaptation to climate change", which has a total of 284 global citations, was the most global cited publication between 2013 and 2020. This article was published in the multidisciplinary, peer-reviewed Climate Policy journal, which has a high impact factor of 5.085 (2020) and publishes research and analysis on all aspects of

climate change policy, including both mitigation and adaptation. In this article Rasul and Sharma (2016) proposed a conceptual framework for evaluating the nexus approach in relation to climate change adaptation. They also outlined the WEF nexus's potential synergies, trade-offs, and opportunities for improving adaptation responses (Rasul and Sharma, 2016).

The second most influential publication on the list is a review article titled "Climate and Southern Africa's Water-Energy-Food nexus" by Conway *et al* (2015) which was published in the nature climate journal. The journal Nature Climate Change publishes innovative research on the science of modern climate change, its effects, and its broader implications for the economy, society, and politics. This is a high impact journal with an impact score of 28.862 (2021). This review paper generated a total citation of 264 between 2015 and 2020. This review paper speculate that Climate change and increased demand associated with socioeconomic development will intensify interdependencies in the water-energy-food nexus, particularly during extreme climate events (Conway *et al*, 2015).

The article "Climate change vulnerability in the food, energy, and water nexus: concerns for agricultural production in Arizona and its urban export supply" by Berardy and Chester (2017), published in environmental research letters was the third highest global impact paper with a total of 66 citations between 2017 and 2020. The journal of Environmental Scientific Letters (ERL) was created to bring together the scientific and policy communities interested in environmental change and management. This is a high impact journal with an impact score of 6.41 (2021). This article constructed a dynamic simulation model of the FEW nexus in Arizona to assess the potential impacts of rising temperatures and interruptions to energy and water supplies on agricultural irrigation requirements, on-farm consumption of energy, and yield. This model was latter used to assess projected increases in consumption of resources and yield loss as well as to identify critical points of intersection between agricultural, water, and energy systems (Berardy and Chester, 2017). Other documents and journal sources with the highest global impact are included in table 3.4.

Table 3.4: The top 10 documents with the greatest global impact ordered by the total number of citation (highest to smallest)

Author, Publication year, Source/journal name	DOI	TC	TC per Year	N _TC
RASUL G, 2016, CLIM POLICY	10.1080/14693062.2015.1029865	284	35.5	2.3
CONWAY D, 2015, NAT CLIM CHANG	10.1038/NCLIMATE2735	264	29.3	2.9
BERARDY A, 2017, ENVIRON RES LETT	10.1088/1748-9326/aa5e6d	66	9.4	1.4
BHAVE AG, 2016, CLIM RISK MANAGE	10.1016/j.crm.2016.09.004	66	8.3	0.5
GONDHALEKAR D, 2017, URBAN CLIM	10.1016/j.uclim.2016.11.004	65	9.3	1.4
NHAMO L, 2020, ENVIRON SCI POLICY	10.1016/j.envsci.2020.04.010	62	15.5	3.8
MPANDELI S, 2018, INT J ENVIRON RES PUBLIC HEALTH	10.3390/ijerph15102306	61	10.2	1.8
VAN NOORDWIJK M, 2018, CURR OPIN ENVIRON SUSTAIN	10.1016/j.cosust.2018.09.003	61	10.2	1.8
PARDOE J, 2018, CLIM POLICY	10.1080/14693062.2017.1386082	55	9.2	1.7
MABHAUDHI T, 2019, INT J ENVIRON RES PUBLIC HEALTH	10.3390/ijerph16162970	52	10.4	2.9

*TC= Total Citations; N= Normalized; DOI= Digital Object Identifier*

### 3.4.4 Top-performing countries, institutions, and collaboration networks in the subject of WEF nexus and climate change adaptation

The top 5 countries with the highest number of publications over the years are shown in Figure 3.6. The number of publications produced in each country between 2013 and 2015 was less than 10, which is extremely low. The production levels in the United States of America (USA), which started publishing in this matter in 2015 and had a sharp curve

between 2018 and 2020 showing a fast-increasing productivity, which indicate a peculiar trend. The first country to report on this subject in 2013 was the United Kingdom (UK), which showed a consistent annual trend of increasing production. South Africa showed a remarkable and continuous production.

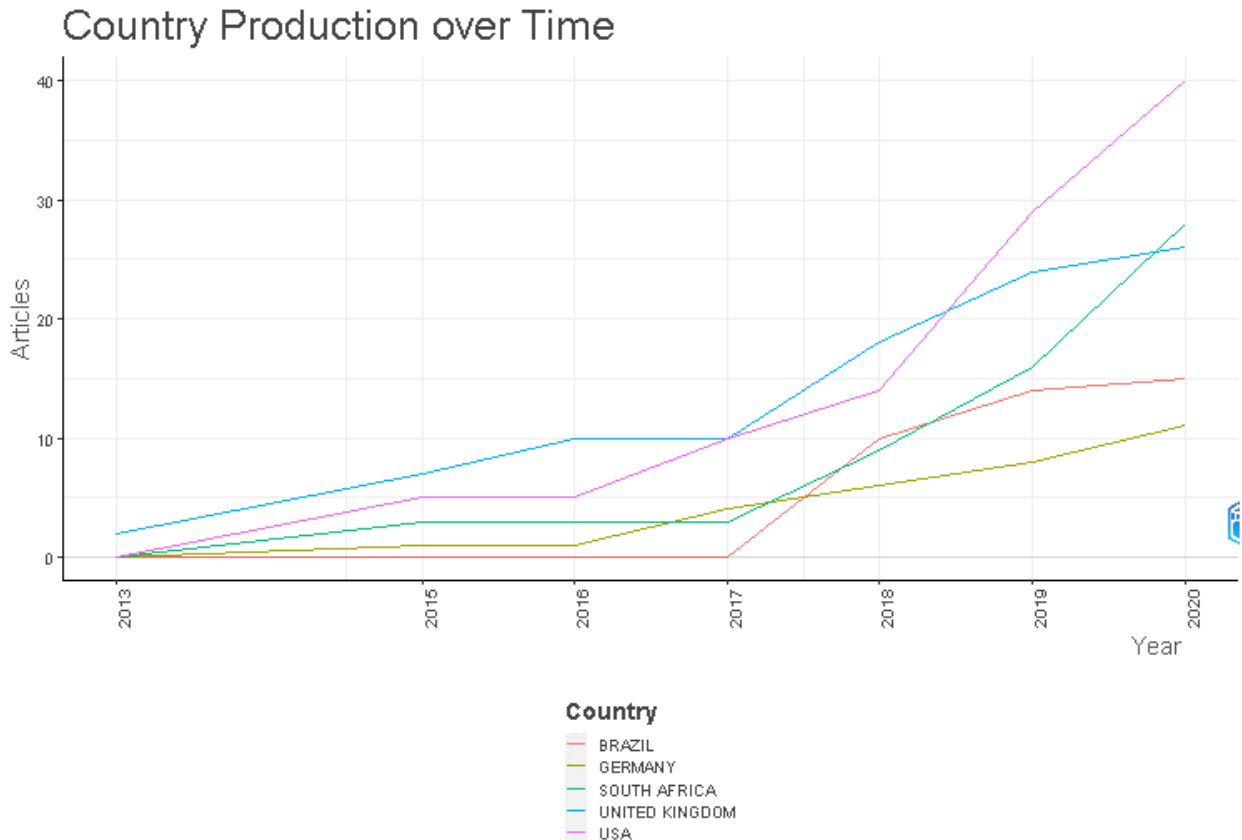


Figure 3.6: The production of the top 5 nations over the years.

It can be observed that the most scholarly literature interlinking WEF nexus and climate change adaptation is produced in Brazil, German, South Africa, UK, and USA while other countries had poor production of less than 10 publications in each country (Figure 3.7). It is not surprising that the USA dominates the top ranking in productivity since it is one of the global leaders in scientific production. However, the significant effort made by South Africa in this research field is remarkable. Understanding the strategic importance of the WEF nexus to the African agenda, the lack of articles in most African countries should be reason for grave concern.

## Country Scientific Production

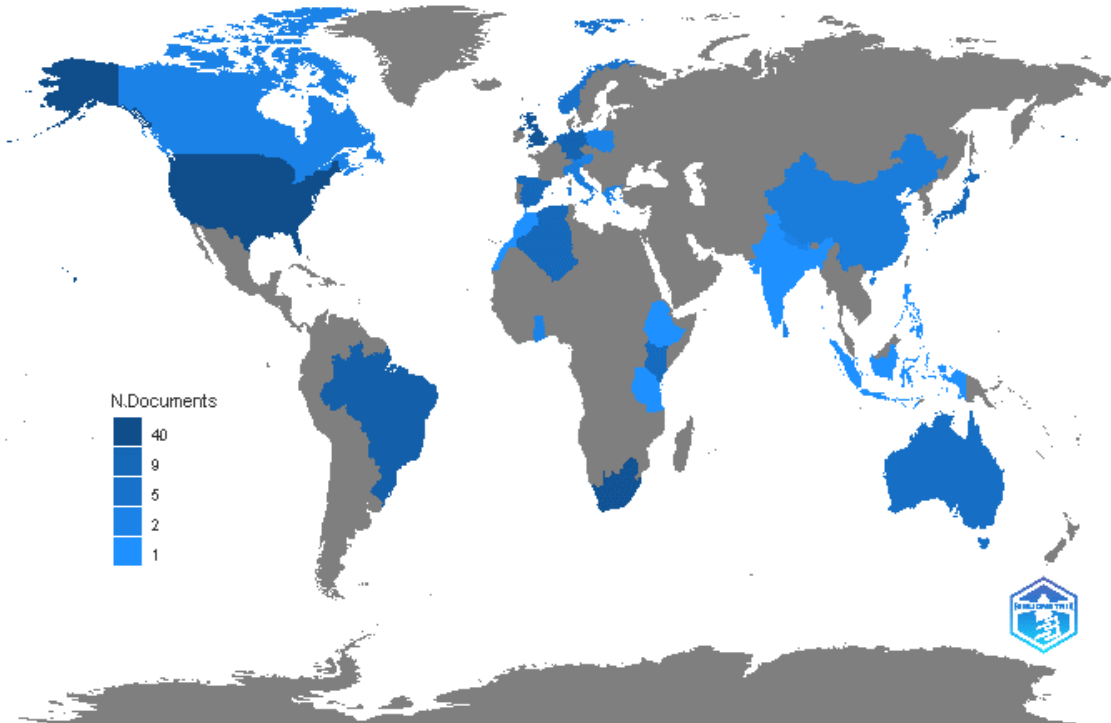


Figure 3.7: The Spatial representation of scientific production by countries.

The scientific output of each country was evaluated based on the author's affiliated country. Table 3.5 shows the top 10 most impactful countries ordered by the total number of citations received (from largest to smallest). It is interesting to see that UK is the country with the most citations in this area of study, receiving more than twice as many as the USA, which had the most publications in this area of study. The UK has the most citations and is the only country on the list with more than 470 citations, indicating that its institutions are the most influential in this field of study. Nepal ranks in the second position with the total citations of 284. It is interesting to notice that the USA, UK, and Germany are among the wealthiest countries in the world based on nominal gross domestic product (GDP) (Table 3.5) and have excellent research output on this subject, suggesting that they have invested more money in research and development activities, which has raised the quality of publications on this subject matter. In contrast, South Africa, Kenya, Ghana, and Nepal, which are developing countries with low nominal GDPs of \$415.32, \$114.6, \$75B and \$36.08B respectively

(Table 3.5), are among the 10 most prominent countries. This shows the urgency for addressing climate change and their commitment to tackling the so-called “triple challenge” of fighting poverty, safe water and procuring energy for all.

Table 3.5: Top 10 most impactful countries in the subject of WEF nexus and climate change adaptation ordered by the total number of citation (highest to smallest)

Country	Continent	GDP (nominal) (billions of \$) 2021	TC	Average Article Citations
UNITED KINGDOM	Europe	3108.42	471	67.3
NEPAL	Asia	36.08	284	284
USA	North America	22939.58	191	17.4
SOUTH AFRICA	Africa	415.32	187	46.8
GERMANY	Europe	4230.17	111	55.5
KENYA	Africa	114.6	61	30.5
GHANA	Africa	75	44	44
AUSTRIA	Europe	481.21	43	21.5
SPAIN	Europe	1439.96	42	21
BRAZIL	South America	1645.84	41	13.7

*GDP= Gross Domestic Product, TC= Total Citations*

The distribution of author-affiliated research institutions that published academic papers on the synthesis of WEF nexus and climate change adaptation between 2013 and 2020 is shown in Figure 3.8. The bibliometric results reveal that University of KwaZulu Natal based in South Africa has been the most prolific publisher of peer-reviewed academic literature during the searched period, with 7 publications authored/co-authored by associated scholars. The following relevant universities are Arizona State University in the USA and Keio University in Japan, each of them has 6 publications in this subject matter. It is impressive that two universities from major international economic giants are among the top institutions actively involved in advancing this discourse. These results also have the fascinating aspect that the University of Kwazulu-Natal in South Africa, a poor developing country, has contributed the most to the body of knowledge on this topic.

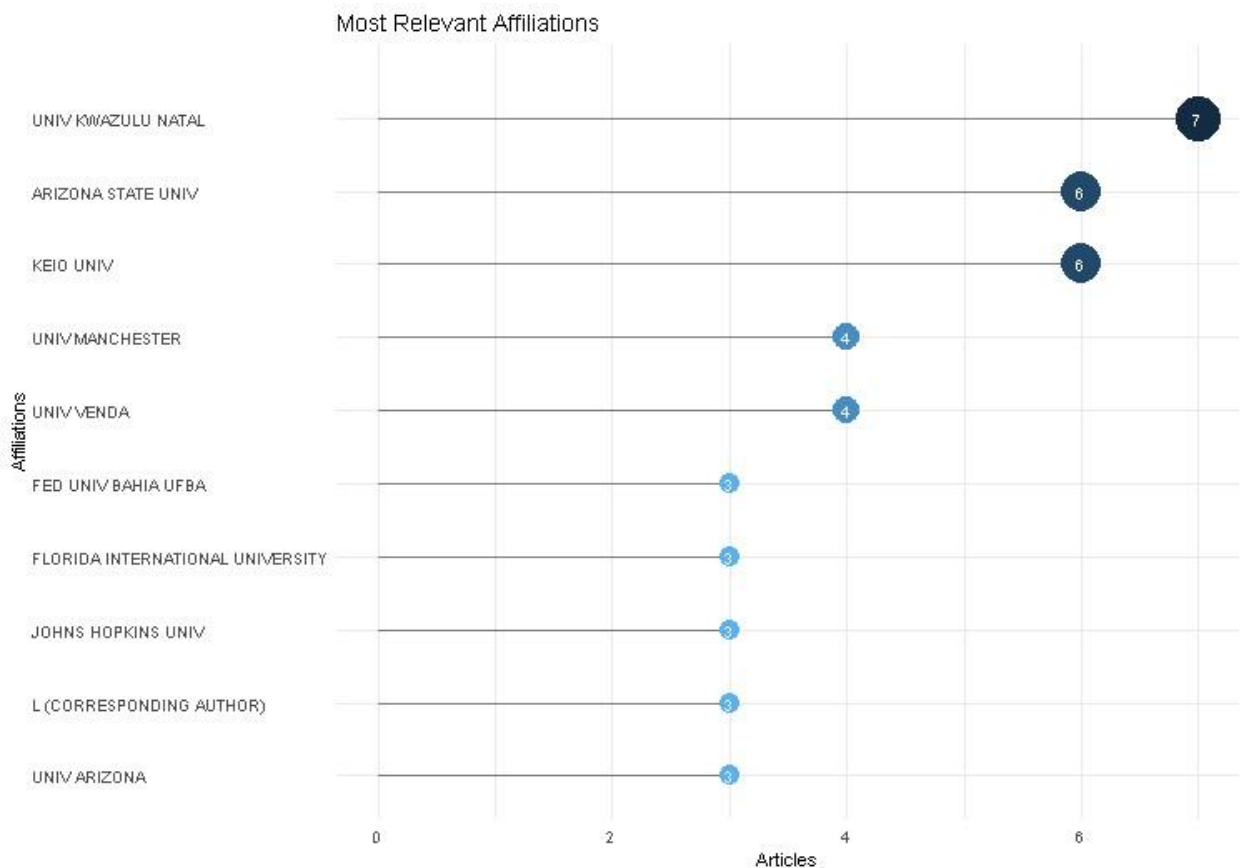


Figure 3.8: The top 10 most relevant institutions.

Some of the articles relating to WEF nexus in the context of climate change adaptation were published under Single Country articles (SCP), while others were published under Multiple Country Publications (MCP) (Figure 9). Collaborations, especially with emerging economies, are appreciated as they can promote the formation of the WEF nexus and climate change research in these regions. It is exciting to see a number of these countries being among the top 10 most productive countries. It is important to note that some of the publications that were published may have come from joint collaborative efforts in which countries like the United Kingdom and Australia took the lead (Botai *et al*, 2021). This shows that collaborations played an important role in advancing this discourse.

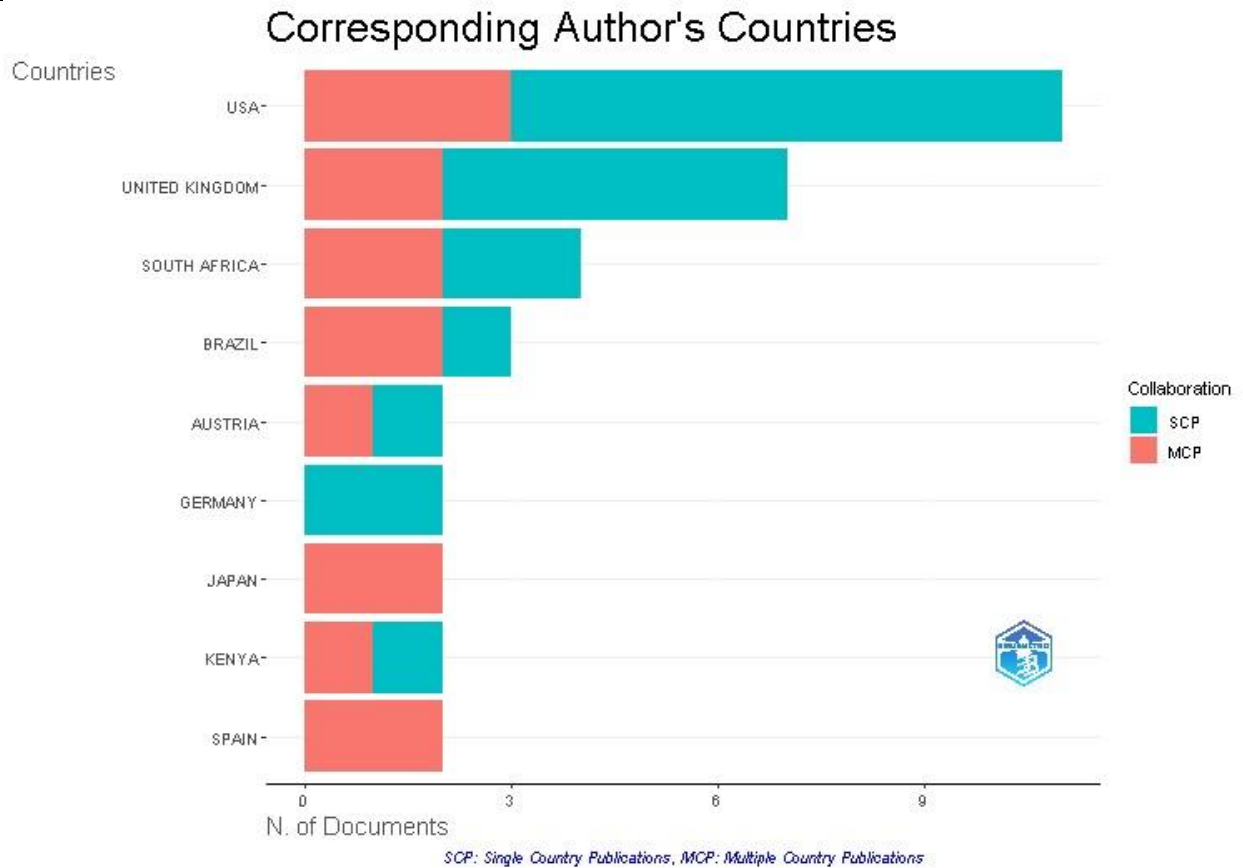


Figure 3.9: The top 10 countries of publications based on corresponding author. *SCP= Single Country Publications, MCP= Multiple Country Publications*

To assess co-authorship and social collaboration analysis, the study probed the social structure component of the bibliometrix, which is an R package offered by biblioshiny (Aria and Cuccurullo, 2017). The social structure is used to explain the collaborations between authors, institutions, and countries (Prell *et al*, 2009; Song *et al*, 2019). In this case nodes in a network represent authors and connecting lines represent relationships between authors. Figure 10 shows that the South African-based authors have established an extremely strong international collaboration. Figure 3.11 shows the existence of strong networks of collaboration among the most prominent authors who have been identified as prolific researchers in this area of study, such as Nhamo and Mabhaudi. The wider and stronger collaborative networks are shown by the thicker lines and larger nodes. These South African-based authors are affiliated with the Water Research Commission (WRC), the University of KwaZulu Natal (UKZN), and the University of Venda (Univen), which are also regarded as the most relevant institutions in this area of study.

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Country Collaboration Map

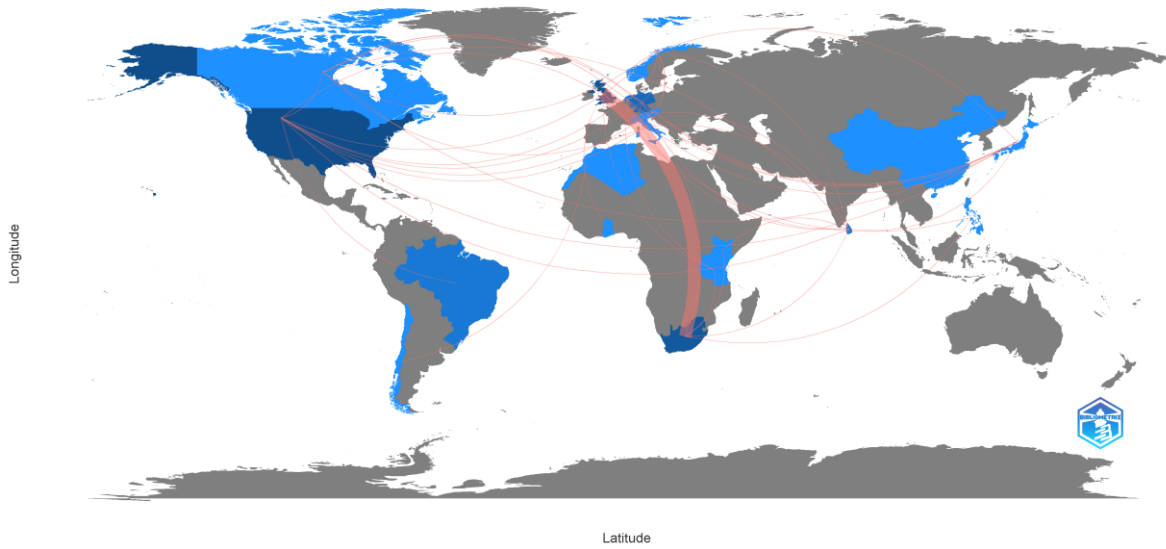


Figure 3.10: International collaboration map.

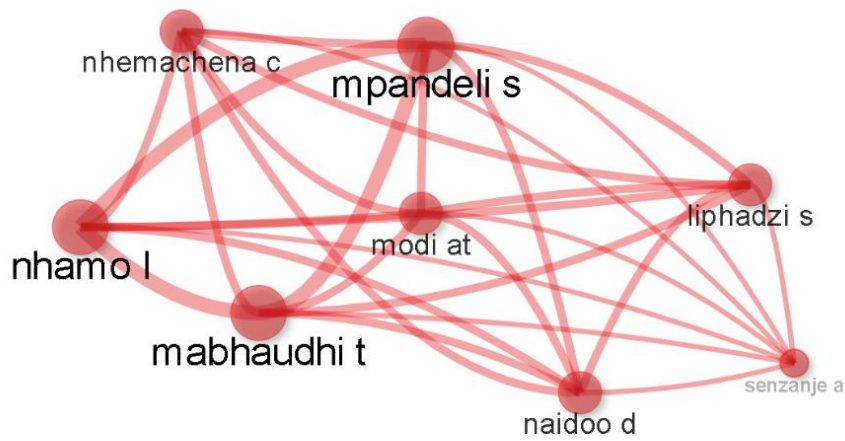


Figure 3.11: Visualization of author's collaboration network.

### 3.4.5 Thematic area of interest in the scope of climate change adaptation and WEF nexus

This section explores the recurring themes in WEF nexus and climate change adaptation research, as well as the areas on which researchers have placed their attention in the past years. This study analysed the author's keywords, trending topics, co-occurrence network and thematic areas of the field to gain insight into whether there is a shift in the topic of discussion among scholars publishing in this matter. Zhao *et al* (2019) asserted that keywords may indicate a literature's subject and clustering analysis of the co-occurrence keywords can reveal the knowledge structure and hotspots in the field of research. Therefore, the current study explored the wordcloud component of bibliometrix offered in biblioshiny to identify main topics and research trends in the subject of WEF nexus and climate change adaptation. Figure 3.12 shows the most commonly use keywords in WEF nexus and climate change adaptation publications. The trending themes include “climate-change”, “adaptation”, “impacts”, “perspective”, “security”, “sustainable development”, “land-use”, “management”, “framework”, “irrigation”, among others (Figure 3.12).



Figure 3.12: Visualization of word-cloud frequently used keywords in the subject of WEF nexus and climate change adaptation.

VOSviewer was used to examine the co-occurrence networks of all keywords from a corpus of scientific literature. Figure 3.13 shows the frequency of co-occurrence of keywords weighted by Total Link Strength (TLS). VOSviewer generates TLS when it maps the research activity of the chosen authors. Table 3.6 provides full details on the keywords in each cluster. Research on climate change adaptation and WEF nexus has drawn uttermost attention to the blue cluster hosted keywords. This is mostly due to the reason that the 6 keywords contained in the blue cluster—climate change, adaptation, framework, sustainable development, water-energy-food nexus, and systems—are fundamental for research on WEF nexus and climate change adaptation. The keywords in the blue cluster provide a strong starting point for research on the WEF nexus and climate change adaptation since they convey the need for strategic intent development and an enabling framework for adaptation to ensure robust collective responses that minimizes trade-offs and maximizes synergies in the WEF nexus.

Scholars interested in WEF nexus and climate change adaptation research also tend to gravitate to the yellow cluster because of its emphasis on sustainable resource management, policy development, and implementation, which are advancing this discourse into areas of political and social influence. When paying attention on the socioeconomic perspective, the 4 keywords found in the yellow cluster have attracted interest from the WEF nexus and climate change adaptation research. The red cluster focuses on 6 keywords concerning with governance issues hindering the WEF nexus implementation. It is interesting that the research on the WEF nexus and climate change adaptation is taking land use contained in the red cluster into consideration, since future climate change adaptation interventions will need to incorporate land use planning if the WEF nexus is successfully observed. The red cluster of key words draws attention to the importance of strengthening the WEF nexus perspective in public sector planning as well as the capacity to identify connections among interdependent sectors and bring these connections to the attention of planning and decision-making processes. Agriculture, energy, effects, mitigation, security, and susceptibility are the most frequently co-occurring terms in the green cluster. Although these keywords have

received attention from scholars, the WEF nexus and climate change adaptation research has paid little consideration to the yellow cluster based on datasets collected in WoS and Scopus.

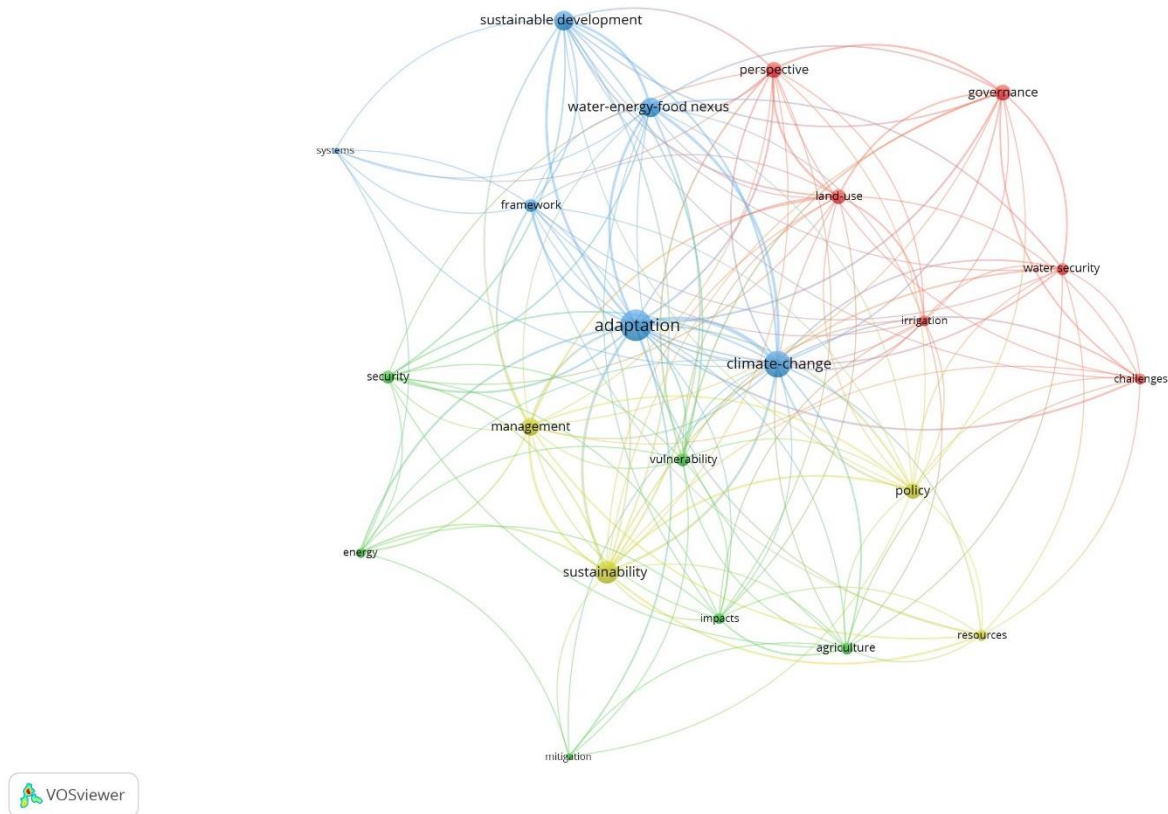


Figure 3.13: Co-occurrence network of keywords showing the occurrence rates of keywords.

Table 3.6: Analysis of the co-occurrence of term clusters

Cluster	NO of Keywords	Selected keywords	Remark
Blue	6	adaptation, climate-change, framework, Sustainable development, systems, water-energy-food nexus	Is given greatest amount of attention in the WEF nexus and climate change adaptation research field.
Yellow	4	Management, policy,	Attracts significant interest

		resources, and sustainability	from scholars in the WEF nexus and climate change research field.
Red	6	Challenges, governance, irrigation, land-use, perspective, and water security	Is given some consideration from academics in the WEF nexus and climate change adaptation research field.
Green	6	Agriculture, energy, impacts, mitigation, security, and vulnerability	Receives little consideration from researchers in the WEF nexus and climate change adaptation research field.

*NO= Number*

The current study used thematic analysis to examine the conceptual structure of the investigated subject matter to better understand the current progress of the research and what lies ahead for its sustainability. Thematic analysis derives themes from the author's keywords and their interconnections (Adeola *et al*, 2022). The themes are distinguished by density and centrality, with density represented by the vertical axis and centrality represented by the horizontal axis. These two characteristics determine whether a topic is relevant and well-developed (Agbo *et al*, 2021). The WEF nexus and climate change adaptation studies are strongly influenced by the motor themes in the upper-right quadrant, which show great centrality and high density (Lulewicz-Sas, 2017) (Figure 3.14). Themes in the upper-left quadrant have gained traction but only internal, making them moderate important in the WEF nexus and climate change adaptation field of research. Themes in the lower left quadrant of the Figure 3.14 are vanishing or no longer relevant in Space of WEF nexus and climate change adaptation. Themes in the lower-right quadrant are important for the future studies on the WEF nexus and climate change adaptation but are still in the early stages (Figure 3.14).

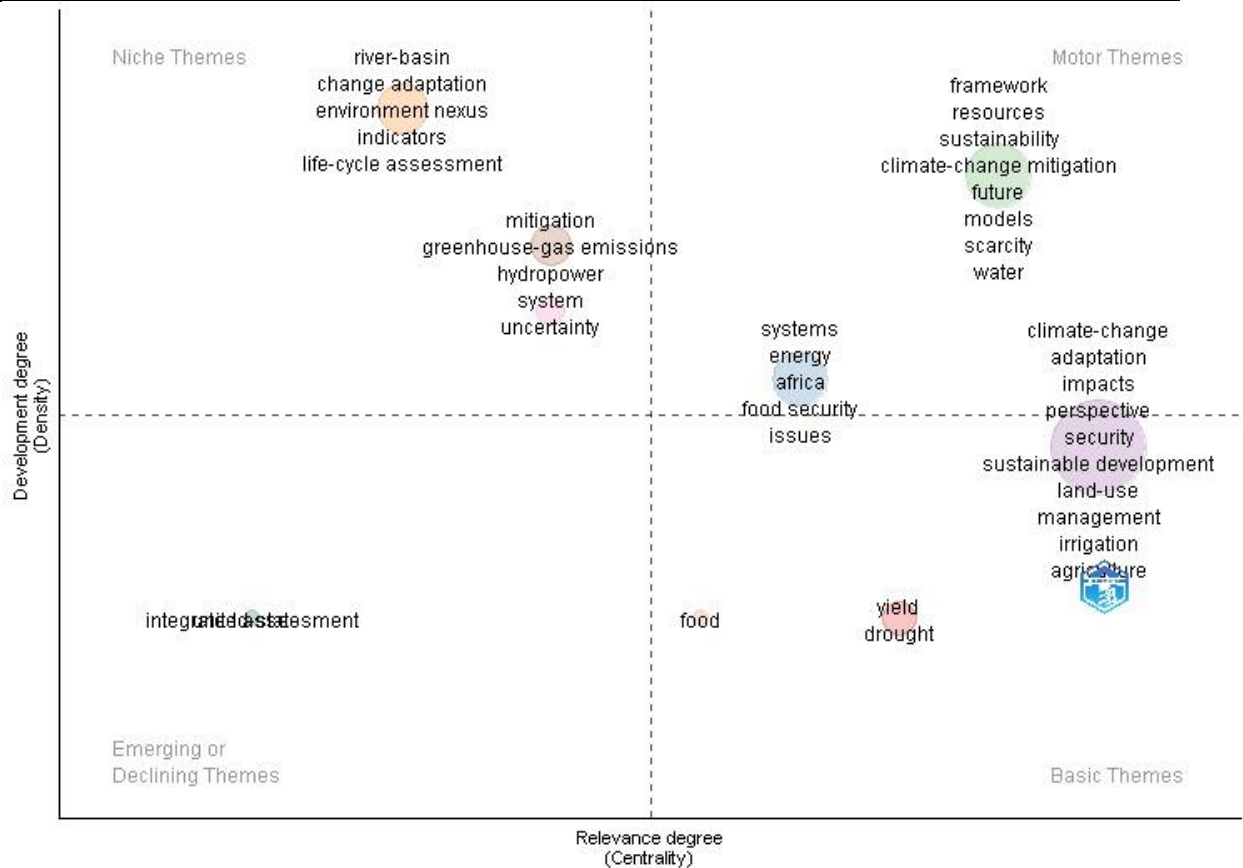


Figure 3.14: Thematic evolution of research on climate change adaptation and the WEF nexus.

### 3.5 CONCLUSION

The WEF nexus approach integrates research, management, and governance across sectors and scales (Local, provincial, and national). It has become a necessary tool to promote sustainable development in view of accumulating evidence of climate change impacts as well as competing demands and limited resources. The WEF nexus adaptation approach is currently anchored in the academic environment. The bibliometric scientific mapping and content analysis of research on the WEF nexus and climate change adaptation reveals the worldwide contributions and hot topics addressed by academics as well as the research goals. Since its inception, the WEF nexus and climate change adaptation research has experienced an increase in scholarly literature, aiming to guide policy development and governance structures in the face of climate change, population expansion, and inequality in access to

resources. The following inferences can be derived from the results of the bibliometric review of research on WEF nexus and climate change adaptation:

- (a) The increasing number of publications shows the pivotal role of the WEF nexus Approach in addressing climate change concerns on a global scale. This is because the WEF nexus provides a viable solution for addressing existing and upcoming resource management, poverty, and inequality concerns in a systematic manner. This highlights the importance of WEF nexus in attaining the SDGs, which are an international agenda that has been endorsed by world leaders, to eradicate poverty and reduce inequality by the year 2030.
- (b) The nexus strategy integrates both multidisciplinary and transdisciplinary aspects. Therefore, research on WEF nexus and climate change adaptation heavily relies on collaboration between researchers from several fields. Collaborations between developed and developing economies are appreciated since they were crucial in promoting the research on WEF nexus and climate change adaptation, especially in poor countries, who are the most vulnerable.
- (c) Results of content analysis exhibit the focus on enacting the WEF nexus adaptation strategy within the policy landscape. However, there is very little empirical support for the present WEF nexus assessment methodologies, and as a result, many people still see the WEF nexus discourse as a solely academic exercise. Scaling is necessary for WEF nexus; Scaling up (effect on laws and regulations); scaling out (effect on larger numbers) scaling deeply (changing the mindset of individuals, institutions, etc.). Geospatial technologies enable real-time monitoring data which helps decision-makers with assessing the state of resources and alleviating the negative impacts of climate change on the environment

**CHAPTER 4                      ANALYSIS OF LAND USE LAND COVER  
DYNAMICS (1990 – 2020) IN MPUMALANGA  
PROVINCE, SOUTH AFRICA: IMPLICATIONS  
FOR THE WEF NEXUS**

This data chapter has been presented at the 13<sup>th</sup> African Association of Remote Sensing of the Environment (AARSE) international conference (2022), that took place in Kigali, Rwanda (<https://aarse2020.org/>). The conference paper has been selected to form part of a “Book Chapter” to be organized and published through “Springer”. This chapter is addressing objective 1

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**4.1 ABSTRACT**

Increasing Land use Land cover (LULC) changes combined with climate variability are imposing significant threats to water, energy, and food security. This situation has serious implications for adaptation strategies that are needed to ensure water, energy and Food (WEF) security in the Mpumalanga Province of South Africa. The aim of this chapter was to analyse the LULC changes that have taken place between 1990 and 2020 and their impacts on natural resources used for food, energy and water. This was achieved using LULC data derived from the South African's National Land Cover (SANLC) data repository for 1990, 2014, 2018 and 2020 datasets. The results revealed that the areas under agriculture, grasslands, shrublands and wetlands decreased from 18.84%, 37.36%, 1.09%, 3.10% in 1990 to 17.06%, 36.63%, 0.54%, 2.66% in year 2014 respectively. The long-term annual rate of change considerably increased for agriculture, barelands and built-up areas from  $-0.41\% \text{ ha}^{-1}$  to  $0.77\% \text{ ha}^{-1}$ ,  $3.19\% \text{ ha}^{-1}$  to  $3.79\% \text{ ha}^{-1}$ ,  $0.75\% \text{ ha}^{-1}$  to  $1.26\% \text{ ha}^{-1}$  respectively within the entire period of study (1990 – 2020). Post-classification comparison of the classified images based on the transition matrix indicated that 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. This study thus provides reliable LULC data that documents the extent and rate of land-use changes that occurred in Mpumalanga Province across the research period extending from 1990 to 2020. A further analysis was done to understand the implications of LULC changes on the WEF resources. The approach adopted in this study 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. This information would be useful in ensuring that the scarce environmental resources (water, energy and food) are optimally allocated in a manner that maximises societal benefit

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

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## 4.2 INTRODUCTION

In recent years, the nexus idea has gained popularity for managing natural resources (Allouche *et al*, 2015). This is mostly attributed to the fact that the nexus research or approaches reflect contemporary ways of investigating links and feedback within and across sectors (Liu *et al*, 2018; Van Zanten and Van Tulder, 2021). One of the many nexuses that have been proposed in the literature is the Water-Energy-Food (WEF) nexus, which offers a useful framework for resolving problems relating to water, energy and food, particularly in climate change-induced environmental challenges, as these sectors are highly vulnerable (Boas *et al*, 2016; Adom *et al*, 2022; Nhamo *et al*, 2018). The WEF nexus strategy is predicated on the premise that it is impossible to effectively address water, energy or food security in isolation without considering the ramifications for the other two (De Laurentis *et al*, 2016). For example, the production of food requires water to grow crops, the management of water (extraction, treatment, and redistribution) requires energy to pump and purify the water, and the creation of electricity, in turn, is reliant on water for cooling and steam generation (Bazilian *et al*, 2011; Flammini *et al*, 2014, Mabhaudi *et al*, 2016, Rasul *et al*, 2016). The WEF nexus strategy can lead to economic development and social security when implemented properly.

However, it has recently become difficult to ensure secure and sustainable WEF resources due to increasing LULC changes, socioeconomic development, and the effects of climate change. 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 these limited resources (Ferroukhi *et al*, 2015). As a result, these challenges will aggravate other factors such as malnutrition, inadequate health care, and migration (Adeyeye *et al*, 2017; Bain *et al*, 2013). Natural and human systems across the world are affected by climate change (Barros *et al*, 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 (Boluwade, 2021). Heat waves, droughts and floods are examples of extreme weather events connected to climate change that affect ecosystems and the services they provide to society (Holtermann and Nandalal, 2016).

Although climate change has an impact on WEF systems, LULC changes may be of equal importance. This can be traced from the previous studies which have drawn much public attention to the significant relationship between LULC changes and WEF nexus resources. For instance, Agidew and Singh (2017) examined the effects of LULC changes on food insecurity in rural households; Fritsche *et al* (2017) examined sustainable energy options and their implications for land use; and Gumindoga *et al* (2018) evaluated the impacts of LULC changes on water availability. This shows that the study of WEF nexus is inextricably linked to the LULC changes. Previous investigations were centred on the relationship of LULC change with individual component of the WEF systems. There are currently very few studies that completely account for how LULC changes affect the WEF nexus resources, especially in the larger picture of climate change.

The current study used a geospatial approach to assess the impact of LULC changes on the WEF nexus resources in the Mpumalanga Province. The Mpumalanga Province represents South Africa's WEF nexus hub. The province currently faces serious competition for land and water use from agriculture and mining operations (Simpson *et al*, 2019). The competing and increasing demands for water, energy and food has led to issues in resource management and the environment (Davies, 2014). The effects of climate change will make this resource trilemma much more challenging. This shows how the government sectors lack appropriate planning and overlook crucial nexus aspects. If this is not addressed properly, it might lead to inappropriate resource allocation, and high levels of unsustainable outcomes, both environmentally and socio-economically.

Questions about the WEF nexus are being addressed using information from earth observation data (Taguta *et al*, 2022). In the past decades, remote sensing has developed into one of the most dependable and consistent data sources for solving social issues (Pitts, 2020). Remote sensing can be applied to identify problems associated with inappropriate use of resources and provide insights into the WEF nexus (Eftelioglu *et al*, 2016). This is because remote sensing provides information on LULC change, which is important for effective land resource management and decision-making (Gomo *et al*, 2018). Understanding LULC changes enables us to better manage WEF nexus resources, increase resource productivity, reduce environmental tension, and promote human security and well-being (Wolde *et al*,

2021). This can help in addressing existing policy and decision-making tensions affecting the land, water, energy and food sectors (Azzam *et al*, 2023).

Many developing countries struggle to provide timely, accurate, and temporally comparable geospatial data to meet management demands (Jha and Chowdary, 2007). Additionally, the data products tend to not be extensively shared between agencies and institutions, and accuracy evaluation can be inadequate (Saah *et al*, 2019). Post-classification comparison is a widely used method for detecting LULC changes and its accuracy depends on the multiplication of individual classification accuracies (Verburg *et al*, 2011). Fortunately, the South African government promotes the exchange and access of geospatial data and information, allowing for the coordination of sustainable spatial development and government efforts throughout the country. Indeed, the Department of Forestry, Fisheries and the Environment (DFFE) provides South African National Land cover (SANL) data with its accuracy reports (accessible at: [https://egis.environment.gov.za/data\\_egis/data\\_download/current](https://egis.environment.gov.za/data_egis/data_download/current)).

The current study provides a scientific foundation for how government departments in charge of delivering WEF services could work together to co-invest available resources and reduce inefficient resource allocation, particularly considering the greater threat posed by climate change. The objectives of this chapter are to (1) classify LULC classes through the lens of WEF nexus and (2) assess the impact of LULC changes on WEF nexus.

### 4.3 MATERIALS AND METHODS

This section describes the methods used to accomplish the objectives of this chapter as well as how they were used. The study employed geospatial methods to understand the impact of LULC changes on WEF nexus resources. The LULC datasets were derived from remote sensing data. Figure 4.1 provides a schematic flow chart diagram explaining the methodology followed in this study.

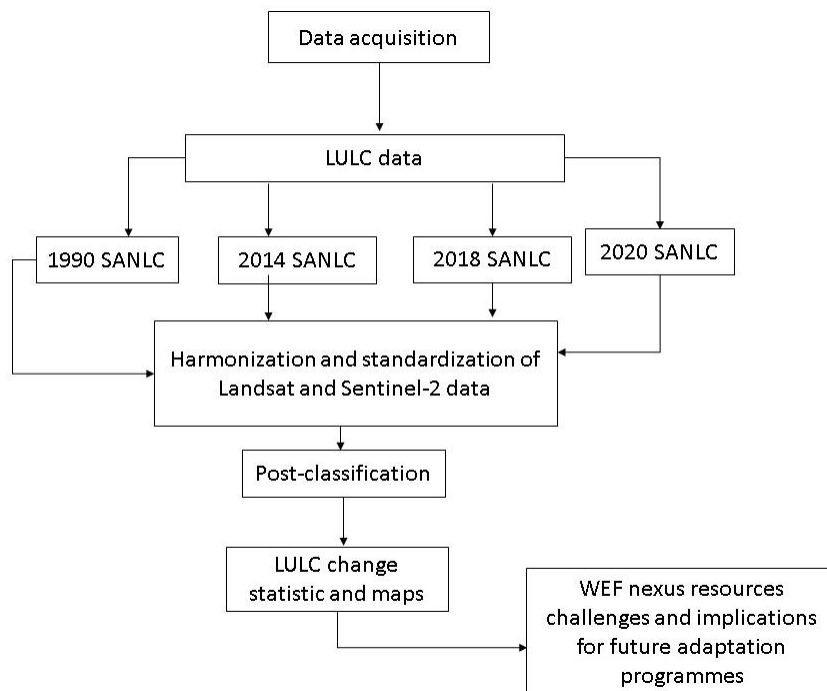


Figure 4.1 Methodological framework for the study (SANLC= South African National Land Cover, LULC= Land use Land Cover).

### 4.3.1 Study Area

The name Mpumalanga, which translates to “place where sun rises,” comes from the Nguni languages (Zulu and Swazi). The province of Mpumalanga is the second smallest in South Africa after Gauteng and is in the northeastern parts of the country (Sigudu *et al*, 2015). The Mpumalanga Province makes up approximately 6.5% of South Africa’s total land surface area with over 4 million residents from different cultural backgrounds (Stats SA, 2011). Mbombela, formerly known as Nelspruit, is the capital of the province. The province is made up of 3 district municipalities, namely Ehlanzeni, Nkangala, and Gert Sibande (Figure 4.2). These are further divided into 18 local municipalities which are Chief Albert Luthuli, Msukaligwa, Mkhondo, Dr Pixley Ka Isaka Seme, Lekwa, Dipaleseng, Govan Mbeki, Victor Khanye, Emalahleni, Steve Tshwete, Emakhazeni, Thembisile Hani, Dr JS Moroka, Thabo Chweu, Bushbuckridge, Nkomazi, City of Mbombela and Umjindi. The mining and agricultural land use sectors play an important role in fight against unemployment and poverty. Other dominant land use patterns in the region include built-up areas (residential,

commercial, industrial, roads and rails) and commercial forestry (see figure 4.2). The two Highveld districts of Nkangala and Gert Sibande have hotter summers and drier, cooler winters, while the Lowveld Ehlanzeni district has a subtropical climate with warm winters (Blom *et al*, 2011).

Poverty remains a serious issue in this province. The province's poverty rate was reported to be 59.1% in 2004 and 50.5% in 2008 (Blom *et al*, 2011). It was also reported that Mpumalanga Province has a Gini coefficient of 0.66, which indicates the social and health inequalities in the province (Profile, 2009). A Gini coefficient is a summary measure of income inequality, which can range from 1 to 0. A case with 1 means that one household makes all the money and other households makes nothing while a case of perfect equality is shown by 0. The study by Matlakala and Von Kallon (2020) noted that Poor service delivery and corruption in this province have caused water shortages and poor infrastructure, leading to communities facing the challenge of having to find ways to clean their own water. The use of various energy sources differs between districts. Nkangala has the highest use of paraffin and electricity for heating and cooking, while Gert Sibande has the highest use of wood and coal (Blom *et al*, 2011). The Mpumalanga Province is expected to have major impacts from climate change in addition to poor allocation of resources.

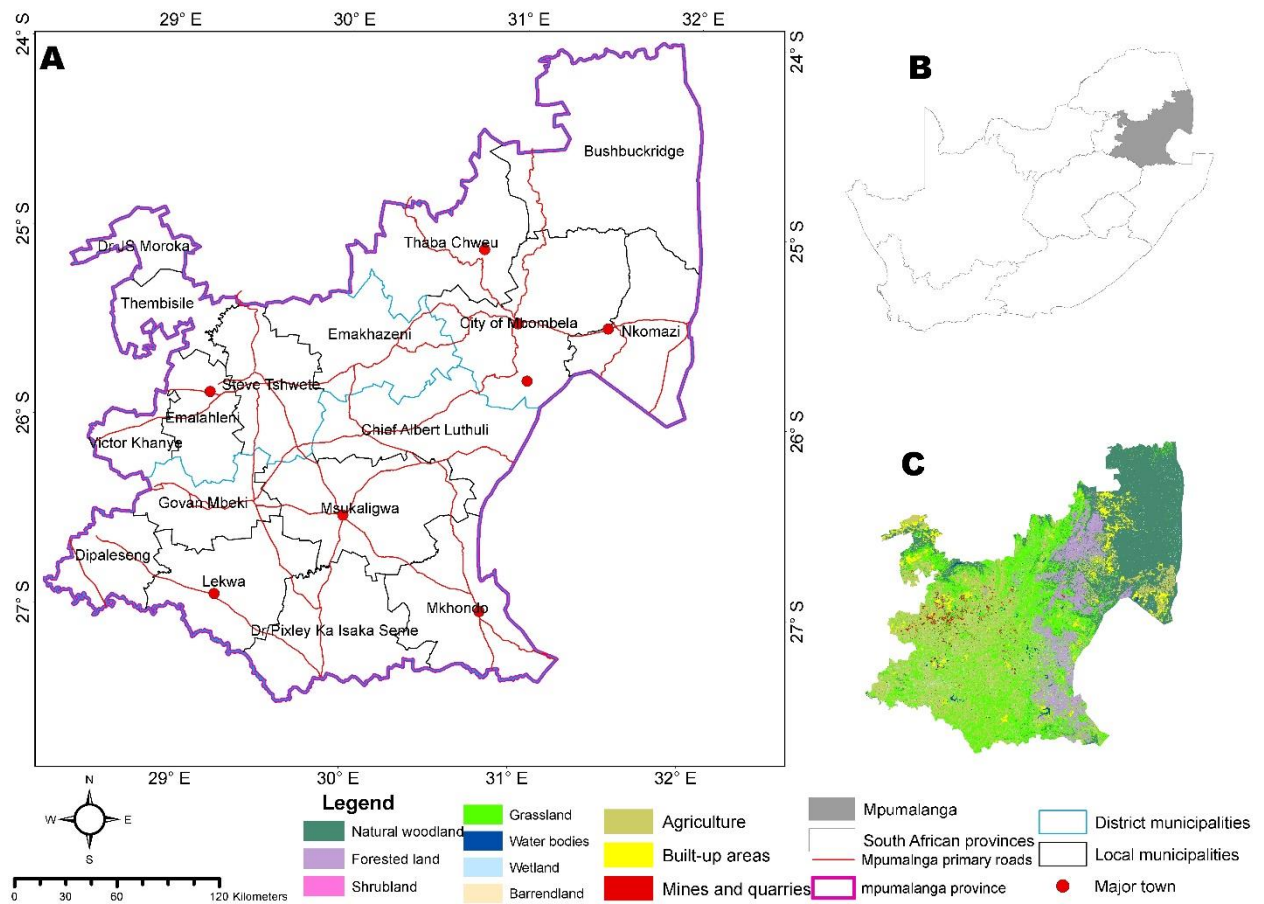


Figure 4.2: Location of the study area. (A) Locality map of the Mpumalanga Province. (B) Mpumalanga Province relative to other provinces in South Africa. (C) Dominant Land use and Land Cover classes in Mpumalanga Province.

### 4.3.2 Data Acquisition

#### 4.3.2.1 Acquisition of land cover maps

LULC data were derived from the SANLC Data repository for 1990, 2014, 2018 and 2020 datasets, acquired from DFFE ([https://egis.environment.gov.za/data\\_egis/data\\_download/current](https://egis.environment.gov.za/data_egis/data_download/current), accessed on the 12<sup>th</sup> July 2022). The SANLC data originates from remote sensing data, i.e., Landsat (1990 SANLC and 2014 SANLC) and Sentinel-2 (2018 SANLC and 2020 SANLC) at 30- and 20-meter spatial resolution, respectively. The Landsat-based SANLC datasets were defined in the Universal Transverse Mercator (UTM) 35 South (S) and World Geodetic System 1984 datum (WGS84), while Sentinel-2 based SANLC datasets were in the Albers

Equal AREA (AEA) projection and World Geodetic system 1984 datum (WGS84). The 1990 SANLC data was derived from Landsat 5 satellite imagery taken between 1989 and 1991 (Musetsho *et al.*, 2021; Tizora, 2018). The 2014 SANLC data was created from Landsat 8 taken between April 2013 and March 2014 (Ngcofe and Thompson, 2015; Mahlayeye, 2017). The SANLC 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 SANLC datasets had 72 classes relative to the 2018 and 2020 SANLC 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 on the 12<sup>th</sup> July 2022). The coordinate reference system for the shapefile was Hartebeesthoek94 Datum and Ellipsoid WGS84. The land cover mapping approach and accuracy assessment for the SANLC datasets is available in the South African national land-cover report and accuracy assessment (accessible at: [https://egis.environment.gov.za/data\\_egis/data\\_download/current](https://egis.environment.gov.za/data_egis/data_download/current)).

### **4.2.3 LULC change mapping for the period of 1990 – 2020**

The current study followed 3 general procedures to assess the LULC changes and evaluate their impacts on the WEF nexus resources: (1) Classifying LULC through the lens of WEF nexus, (2) change detection, and (3) draws attention to the LULC types that are strongly linked to the WEF nexus.

#### **4.2.3.1 Reprojection, resampling and reclassification of land cover maps**

The Sentinel-2 based SANLC datasets and Mpumalanga Province shapefile were reprojected into UTM zone 35 South to work with the SANLC datasets derived from Landsat imagery. The reprojection was done using a projection tool on ArcMap 10.4.1. SANLC datasets were confined into the spatial extent of Mpumalanga shapefile using the clipping tool from data

management in ArcMap 10.4.1. The benefits and drawbacks of combining Sentinel-2 and Landsat images were carefully considered, as the study area's LULC change was analyzed using directly comparable LULC datasets that are derived from Landsat and Sentinel-2 images (Mandanici, 2016). Alhedyan (2021) state 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. To accurately detect LULC changes using multi-sensor images, the collection of images must come from similar seasons, cover the same area, and have the same spectral and spatial resolution.

Sentinel-2 based SANLC datasets were resampled to 30-meter spatial resolution for compatibility with Landsat-based SANLC datasets (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 (Roy *et al*, 2016). To facilitate evaluating and assessing LULC trends, the SANLC classes were reclassified into 10 classes and those that are directly linked to the WEF nexus. 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(A.2.1). The legend was harmonized and standardized to ensure comparability (Table 4.1).

Table 4.1: Harmonized and standardized LULC classes used for change detection analysis.

Land cover types	New classes	SANLC 1990 and 2014*	SANLC 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*

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. Appendix A.2.2 indicates the relationships between different LULC categories in the study area and WEF attributes.

#### 4.2.3.2 LULC change detection

Change detection is the process of examining an object at different times to detect changes in its state (Singh, 1989). It lays the foundation for a better understanding of the links and interactions between humans and natural events, allowing for improved resource management and use (Lu, 2004). Following the methodological approach of previous studies (Bekele and Yirsaw, 2019; 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 PCC change detection (Yang and Wen, 2011). The PCC approach uses overlay functions to create a cross-tabulation matrix (LULC change transition matrix). In this study, 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:

$$\Delta C = \left( \frac{A_f - A_i}{A_i} \right) * 100 \quad (1)$$

Where  $A_i$  denotes the initial year area,  $A_f$  denotes the final year, and  $\Delta C$  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 (Puyravard, 2003):

$$\Delta R = \left( \frac{1}{t_2 - t_1} \right) \ln \left( \frac{A_2}{A_1} \right) \quad (2)$$

where  $\Delta R$  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.

## 4.4 RESULTS AND DISCUSSION

This section will report results on: (1) analysis of LULC change and its impacts on WEF nexus resources over a 30-year period (1990 – 2020) in Mpumalanga Province, (2) WEF nexus resources challenges and implications for future climate change adaptation programmes.

### 4.4.1 Accuracy assessment for the LULC change

No accuracy assessment was conducted on the 1990 SANLC dataset due to lack of suitable reference data. However, the map accuracies obtained for the 2013–14 dataset may be used as an accurate reflection of the potential mapping accuracies attained for the 1990 dataset since the 1990 SANLC data was created using the same mapping and modeling processes and image formats (Geoterraimage, 2015). This was calculated using 6415 samples (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 (Geoterraimage, 2015). The 2018 SANLC dataset has an overall map accuracy of 91.32% derived from 6570 reference points (Thompson, 2019) while the 2020 SANLC has an overall accuracy of 85.47% based on 6835 reference points (Thompson, 2020).

## 4.4.2 Assessing LULC change for 30-year period in the Mpumalanga Province

### 4.4.2.1 LULC change Pattern for the period 1990 – 2020

Figure 4.3 shows LULC maps for 10 LULC classes that are being investigated. During the entire study period (1990 – 2020), agriculture, grasslands, Mines and quarries, natural woodlands and plantations were predominant LULC classes (Figure 4.4).

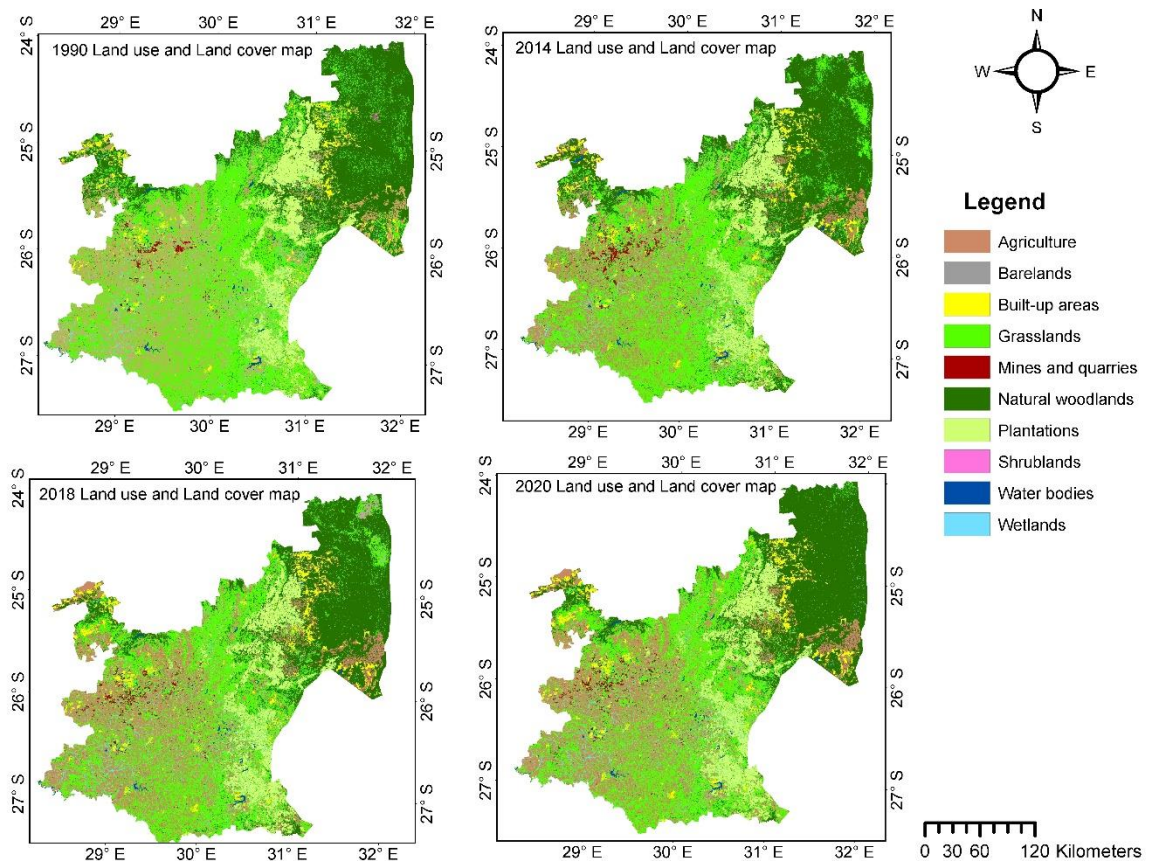


Figure 4.3: LULC maps for 1990, 2014, 2018 and 2020

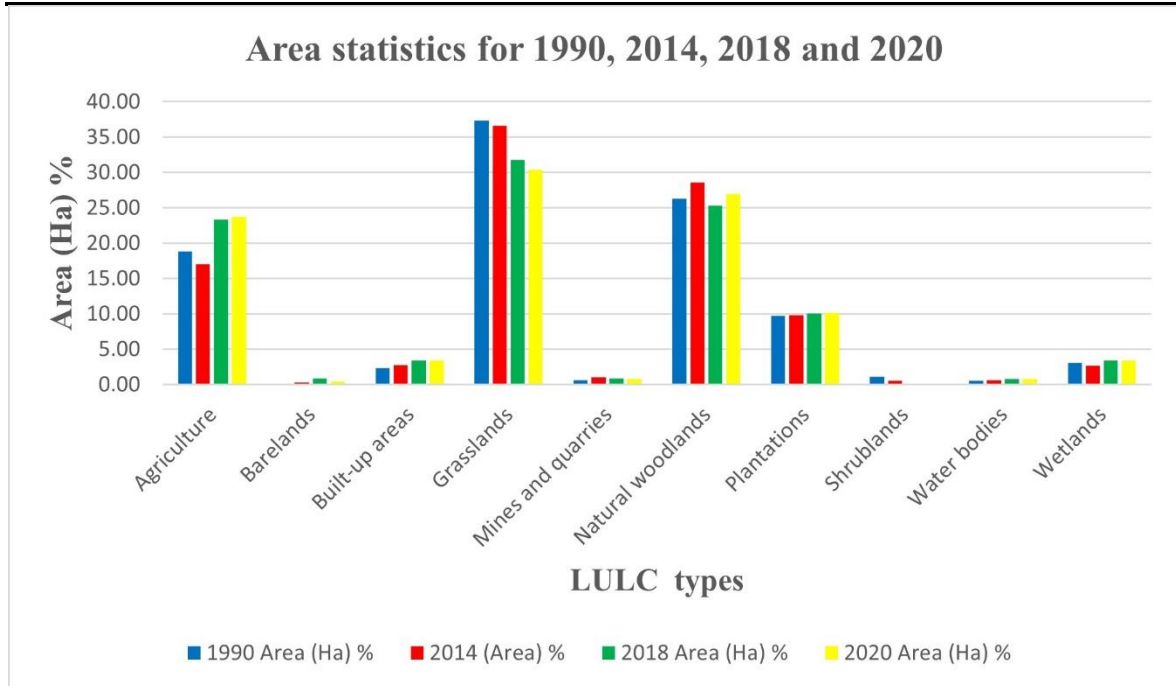


Figure 4.4: Area statistics of LULC maps for various years

In 1990, agriculture, barelands, built-up areas, grasslands, mines and quarries, natural woodlands, plantations, shrublands, water bodies and wetlands covered 18.84%, 0.15%, 2.33%, 37.36%, 0.61%, 26.29%, 9.70%, 1.09%, 0.53% and 3.10% of the study area respectively (Table 4.3). The LULC areas under agriculture, grasslands, shrublands, wetlands decreased from 18.84% (1443997.4 ha), 37.36% (2863977.66 ha), 1.09% (83336.31 ha), 3.10% (237623.85 ha) in 1990 to 17.06% (1308009.69 ha), 36.63% (2808024.57 ha), 0.54% (41641.38 ha), 2.66% (204214.77ha) in 2014 respectively. On contrary, barelands, built-up areas, mines and quarries, natural woodlands, plantations, water increased from 0.15% (11430.18 ha), 2.33% (178984.26 ha), 0.61% (46508.13 ha), 9.70% (743359.05 ha), 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), 0.59% (45608.49 ha) in year 2014 respectively. The observed changes 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). The majority of 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 wood resources to the economy of the Mpumalanga Province. The province of Mpumalanga 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% in 2014, increased rapidly to 23.48% in 2018. For barelands, built-up areas, plantations, and water bodies the trend continued the same up to 2018. 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- 2020), the LULC with increased areas are agriculture, built-up areas, natural woodlands from 23.38%, 3.40%, 25.30% in 2018 to 23.73%, 3.41%, 26.92% respectively. Between 2018 and 2020, there was a 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) show that the LULC areas under agriculture, built-up areas, mines and quarries increased from 18.84% (1443997.44ha), 2.33% (178984.26ha), 0.61% in 1990 to 23.73% (1818913.23ha), 3.41% (261126.81ha), 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).

## CHAPTER 4

## SECOND DATA CHAPTER

Table 4.2: LULC distribution of the Mpumalanga Province

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) %
<b>Agriculture</b>	1443997.44	18.84	1308009.69	17.06	1792095.48	23.38	1818913.23	23.73
<b>Barelands</b>	11430.18	0.15	24615.27	0.32	67543.83	0.88	35719.65	0.47
<b>Built-up areas</b>	178984.26	2.33	214485.84	2.80	260757.45	3.40	261126.81	3.41
<b>Grasslands</b>	2863977.66	37.36	2808024.57	36.63	2440055.88	31.83	2329362.18	30.39
<b>Mines and quarries</b>	46508.13	0.61	77710.5	1.01	64710.63	0.84	60506.1	0.79
<b>Natural woodlands</b>	2015718.39	26.29	2189381.31	28.56	1939256.82	25.30	2063747.52	26.92
<b>Plantations</b>	743359.05	9.70	752154.66	9.81	769851	10.04	776071.98	10.12
<b>Shrublands</b>	83336.31	1.09	41641.38	0.54	10199.43	0.13	44.55	0.00
<b>Water bodies</b>	40911.21	0.53	45608.49	0.59	59150.7	0.77	58541.85	0.76

## CHAPTER 4

## SECOND DATA CHAPTER

<b>Wetlands</b>	237623.85	3.10	204214.77	2.66	262225.26	3.42	261812.61	3.42
<b>Total</b>	<b>7665846.48</b>	<b>100.00</b>	<b>7665846.48</b>	<b>100.00</b>	<b>7665846.48</b>	<b>100.00</b>	<b>7665846.48</b>	<b>100.00</b>

#### 4.4.2.2 Net gain, LULC area percentage, percentage increase/decrease annual rate of change

During the study period (1990 – 2020), there have been significant net changes in gains and losses for LULC classes in the study area (Figure 4.5). Figure 4.5 depicts the net changes in gains and losses for each LULC class for the periods 1990–2014, 2014–2018, 2018–2020, and 1990–2020. Grasslands and shrublands lost a significant amount of area between 1990 and 2020 (534615.48 ha and 83291.76 ha, respectively), whereas agriculture, built-up areas, mines and quarries gradually increased. During the study period (2018 – 2020), the natural woodlands and plantations gained by 124490 ha and 6220.98 ha of land respectively. In the same period, barelands experienced considerable losses. From 2014 to 2018, agriculture experienced the largest expansion (484085.79 ha), while grasslands (367968.69 ha) and natural forests (250124.49 ha) had the largest losses. Between 1990 and 2014, the built-up areas and mines and quarries gained 196591.58 ha and 31202.37 ha respectively. In the same period, the highest loss was observed in the agriculture (1313987.75 ha), followed by shrublands (41694.93 ha), grasslands (55953.09 ha) and wetlands (33409.08 ha).

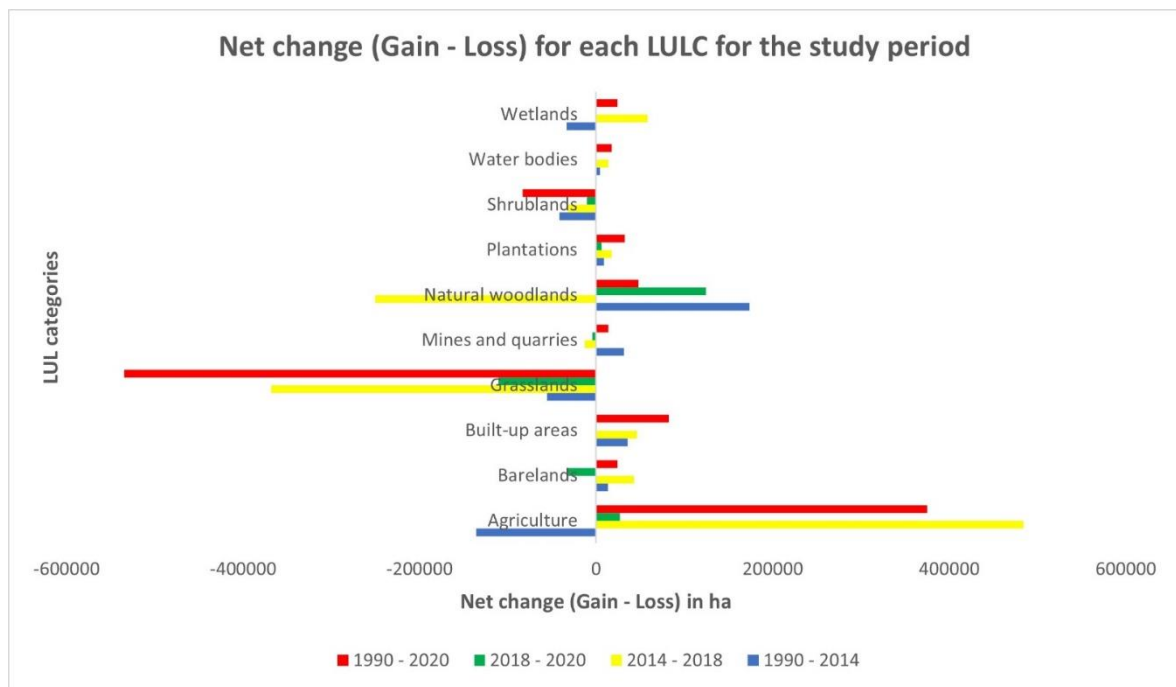


Figure 4.5: Net change for each LULC category for the study period

During the initial phase of the study period (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<sup>-1</sup>, 2.14% ha<sup>-1</sup> and 0.75% ha<sup>-1</sup> respectively. On the contrary, shrublands, wetlands and agriculture have declined by 50.03%, 14.06% and 9.42% at -2.89% ha<sup>-1</sup>, -0.63% ha<sup>-1</sup> and -0.41% ha<sup>-1</sup> respectively (Table 4.3). The notable increase in barelands areas between 1990 and 2014 is probably caused by the removal of natural vegetation and use of heavy machinery for mining and agriculture.

Table 4.3: LULC area percentage, net change percentage, percentage increase/decrease and annual rate of change (1990-2014)

LULC Names	1990 Area %	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

During the second phase of the study (2014 – 2018), the annual rate of change demonstrated a different shifting trend for most LULC classes (Table 4.4). For agriculture and wetlands, the long-term annual rate of change has significantly risen from -0.41% ha<sup>-1</sup> to 7.9% ha<sup>-1</sup> and -0.63% ha<sup>-1</sup> to 6.3% ha<sup>-1</sup> respectively, whereas annual rate of change has significantly declined for mines and quarries and natural woodlands from 2.14% ha<sup>-1</sup> to -4.6% ha<sup>-1</sup> and 0.34% ha<sup>-1</sup> to -3% ha<sup>-1</sup> respectively. 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<sup>-1</sup> to 25.2% ha<sup>-1</sup> and 0.75% ha<sup>-1</sup> to 4.9% ha<sup>-1</sup>. Mining locations are popular destinations for migrants because of 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 demand for infrastructure, such buildings and roads, resulting from an increasing population, may be associated with the expansion of built-up areas. During the same period, barelands and built-up areas occupied top positions in terms of percentage increase.

Table 4.4: 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	Percentage 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

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<sup>-1</sup>, from land area 67543.83 ha to 35719.65 ha (Table 4.5). The water bodies and wetlands have also experienced a drastically loss by -1.03% and -0.16 at an annual rate of change -0.08% ha<sup>-1</sup> and -0.51 respectively.

Table 4.5: 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	Percentage 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

Throughout the duration of the study (1990 – 2020), shrublands declined by 99.95% at annual rate of change of 25.11% ha<sup>-1</sup> which was the largest loss over the considered period, and it is followed by grasslands class which declined by 18.67% at an annual rate of change of 0.69% ha<sup>-1</sup> (Table 4.6). The shrublands class is the most LULC class that experienced drastically loss throughout the study period. The decline in grasslands and shrublands may also be attributed to afforestation because of the serious damage it causes to the biodiversity of the province of Mpumalanga (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 which makes grassland bird species vulnerable. Barelands, built-up areas, agriculture and mines and quarries are the most LULC classes that experienced significant gains in the study area.

Table 4.6: 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
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

#### 4.4.2.3 LULC CHANGE (TRANSITION) MATRIX

The LULC change matrix (Table 4.7, Table 4.8, Table 4.9, and Table 4.10) shows the distribution of major transitions in the 10 LULC categories from 1990 – 2014, 2014 – 2018, 2018 – 2020 and 1990 – 2020. The results of LULC change matrix reveal significant LULC changes in Mpumalanga.

Table 4.7 shows that between 1990 and 2014, the conversion area of agriculture was 25.1% (310566.04 ha), with 13.62% converted to grasslands 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.

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Table 4.7: LULC change matrix between 1990 and 2014

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

Between 2014 and 2018, about 88.73% (1160657.1 ha) of agriculture remained unchanged, while the remaining agricultural area of 11.26% (147352.59 ha) 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 4.8). In the same period 83.88%, 8.12%, 34.11%, 28.72%, 14.45%, 2.93% of total land areas of barelands, built-up areas, grasslands, natural woodlands, plantations, wetlands were changed to different classes. Approximately over 51.79% (40253.22 ha) of mines and quarries remained unchanged, while 37457.28 ha was converted to other classes, with the majority going 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 4.8: LULC change matrix between 2014 and 2018

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

Table 4.9 shows the transition matrix between 2018 and 2020. A total area of 7.41% (568655.37) ha has changed during the study period. Agriculture, mines and quarries, natural woodlands, shrublands, plantations, water bodies are among the classes that changed to other LULC classes accounting for 1.53%, 24.19%, 6.95%, 99.93%, 2.77%, 12.92%, respectively. During this period shrublands experienced highest transition, with the majority converting to natural woodlands (88.23%) and grasslands (11.19%). Majority of natural woodlands, plantations and water bodies classes converted 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.

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Table 4.9: LULC change matrix between 2018 and 2020

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

Table 4.10 demonstrates that shrublands and barelands experienced the most conversions, with 99.99% and 87.12% of their LULC areas changed into other classes respectively. The transition matrix (Table 4.13) shows that 55.56% of mines and quarries in 1990 had been converted into grasslands in 2020. The results also reveal that 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 caused energy and food production in Mpumalanga Province to compete for the use of land and water. Coal mining and agricultural production have a negative impact on the environment, particularly on soil composition, water quality and natural habitats (Haddaway *et al*, 2019; Rohila *et al*, 2017).

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Table 4.10: LULC change matrix between 1990 and 2020

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

### 4.4.3 Implications of LULC dynamics on the WEF

Over the past ages, Humans have altered the landscape for settlements, infrastructures, resource extraction and agriculture (Kirch, 2005; Ellis *et al*, 2013; Winkler, 2021). There has been a significant increase in the extent, intensity and rate of LULC Changes throughout the previous few decades (Hassan *et al*, 2016). The growing human effect on natural resources has made it evident that LULC changes are associated with major environmental challenges. WEF systems depend on land, therefore as these systems evolve, LULC changes can have both positive and negative effects. 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. This section will examine the impact of LULC changes on WEF resources in the Mpumalanga Province.

#### 4.4.3.1 Implications of LULC dynamics 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). The majority of South Africa’s coalfields, as well as the majority of coal-fired power plants, are in Mpumalanga Province (Mathu and Chinomona, 2013). The findings of the LULC change detection show that considerable changes in Mining areas occurred during the 30-year research period (1990 – 2020). Mining and quarries increased in the Nkangala (Northwestern region) and Gert Sibanda (Southwestern region) district municipalities between 1990 and 2020. 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 (Northeastern region) district municipality remained constant during the study period, although a significant loss was noted in the western Nkangala district (A.2.3). This might be linked to coal mining activities in the Nkangala district municipality, as well as the harvesting of fuelwood, as the region is primarily rural. Mpumalanga Province has the most forestry plantations in South Africa, followed by KwaZulu-Natal. The Ehlanzeni and Gert Sibande districts represent Mpumalanga’s forestry epicentre. Appendix (A.2.3) shows that

the majority of forestry lands remained unaltered over the study period, with modest losses in Ehlanzeni district and tiny gains in Gert Sibande district. The severe drop in shrublands seen might be linked to increased human population, frequent drought, changes in settlement and land tenure patterns and changes as a result of alien plant species invasion. Shrublands and woodlands are potential sources of renewable energy, therefore this might cause a severe impact on energy sources.

#### **4.4.3.2 Implications of LULC dynamics on Food sources**

The agricultural sector plays an essential role in stimulating economic development, supporting livelihoods and securing food for the people of the Mpumalanga Province. The findings of LULC change detection showed that the overall area of land used for agriculture, including both large-scale and small-scale farms, is approximately 181891.23 ha, representing 23.73% of Mpumalanga Province's surface area (7665846.48 ha). Commercial agricultural land in the study area comprised mainly grazing land and arable land. Grazing land is used for livestock and game farming, and arable land is used for crop production. A.2.4 shows that The Gert Sibande (Southwestern region) district accounted for the largest share of Mpumalanga Province's agricultural land, followed by Nkangala (Northwestern region) and Ehlanzeni (Northeastern region) districts. 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 (A.2.4). The agricultural sector in the study area is dictated by several important drivers and processes of change affecting its ability to ensure food security for the region. The LULC change results shows the ongoing expansion of coal mines and their use of fertile land for mining production poses serious challenges for food security in the study area.

#### **4.4.3.3 Implications of LULC dynamics on water sources**

It has been estimated that South Africa's water supply won't be sufficient to fulfill the demand by 2025 (Mnguni, 2020). Waterbody classes were more stable across the years of the analysis (A.2.5). There is also a subtle increase in the wetland class. The Upper Olifants

Catchment, which is the home of eight coal mining operations, has been identified by the Department of Human Settlements, Water & Sanitation 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 Province was published by Ololade *et al* (2017). The investigation identified several problems, such as the province's extensive use of mining and irrigated agriculture, which are depleting the province's water supply and quality. In addition, Mpumalanga Province's water security is greatly affected by the regular draining of wetlands for agricultural purposes, the negative impact of plantation forestry on the water table, and the effects of poorly managed open-pit mining on the quantity and quality of water flowing into and out of wetlands and rivers.

#### 4.5 CONCLUSION

It is important to have a comprehensive understanding of LULC changes and its implications on the WEF nexus resources. This is important for enhancing intergovernmental planning and coordination by the government departments in charge of providing service delivery of WEF resources. The DFFE provides reliable and up-to-date information on South Africa's LULC for strategic planning, resource management, and environmental research. This study used the SANLC datasets to produce wall-to-wall mapping of land use for the Mpumalanga Province. The SANLC data originates from remote sensing data. The study employed GIS and remote sensing techniques to understand the impact of LULC change on WEF nexus. The results obtained from the analysis should enable Departments responsible for the governance of the components of the WEF nexus to render services related to the WEF to and for the communities in their jurisdictions more efficiently. Earth observation data and geospatial methods have been shown to be an effective and dependable source of vital information to support natural resource managers in integrating their strategies and plans for competing land use objectives. The results of the current study showed that the major LULC changes in Mpumalanga are related to mining, agriculture, grasslands, woodlands, and built-up areas. All of these changes have a direct impact on water supplies, energy sources, and food production. The results of the analysis 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 implications on WEF nexus resources can give government decision-makers a scientific foundation to improve the current land development and planning policies.
- (c) GIS and remote sensing have the potential to be a reliable and efficient source of essential information to address the present tensions between policies and decisions in the food, water, energy, and land sectors that aim to increase resource productivity, reduce environmental pressure, and improve human security and well-being.
- (d) There is the need to improve cross-sector cooperation and coherence of efforts in order to properly tackle the WEF nexus-based challenges.

**CHAPTER 5                    A GEOSPATIAL FRAMEWORK FOR THE  
SUSTAINABLE IMPLEMENTATION OF THE  
WATER-ENERGY-FOOD NEXUS CLIMATE  
CHANGE ADAPTATION INTERVENTIONS**

The results of this data chapter were presented at the Climate Change Research Conference hosted by the City of Tshwane and Tshwane University of Technology (TUT) on the 9-10 March 2023

(<https://www.tshwane.gov.za/?p=51792#:~:text=This%20two%2Dday%20conference%20will,City%20on%20being%20climate%2Dresilient>). This chapter is addressing objective 2 and 3 of the study.

## 5.1 ABSTRACT

There is no common understanding of how the Water-Energy-Food (WEF) nexus can contribute to successful adaptation in the Mpumalanga province's circumstances. The study area epitomizes the challenges of sustaining the WEF resources from the impacts of climate change. The aim of this study is to find a practical governance framework that supports the sustainable implementation of the WEF nexus climate change adaptation interventions. The Generalized Linear Model (GLM) through logistic regression was implemented using 3 scenarios with the help of R studio, an integrated development environment for the R programming language. Scenario 1: Model based on environmental variables only; Scenario 2: socio-economic variables only and scenario 3: combining environmental and socio-economic variables. The logistic regression model was used to determine if socioeconomic and environmental drivers could predict the location of WEF nexus based-climate change adaptation interventions. Based drivers and spatial prediction, a framework or model to synthesize and prioritize potential areas of climate change adaptation intervention or action in Mpumalanga Province was developed. The study used the Receiver Operating Characteristic (ROC) and Area Under Curve (AUCs) to evaluate the performance of the model. All models were statistically significant, with AUC = 72% for scenario 1, 67% for scenario 2, and 73% for scenario 3. The results revealed that the northeastern region and northwestern region of Mpumalanga Province should be prioritize for climate change adaptation interventions. These regions are particularly vulnerable to extreme weather events, and the expansion of the coal mining sector in these areas poses a threat to agriculture. This study was very instrumental in the improvement of a national database for Mpumalanga province, where the adaptation related projects (i.e., completed, current and planned) are being implemented, by whom, at what scale, and at what cost? The results obtained in this chapter indicate that the use of geospatial tools can be useful in the planning and prioritization of activities related to climate change adaptation. The use of earth observation data and geospatial techniques in the synthesis and understanding of climate change adaptation through the lens of WEF advances the application of space science and technology, particularly Fourth Industrial Revolution (4IR), for impact on society.

Keywords: Water-Energy-Food nexus; adaptation; logistic regression model

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## 5.2 INTRODUCTION

While our understanding of climate change and its potential impacts has improved, there is still a lack of practical guidance for adaptation (Vogel *et al*, 2019). This is because of 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). Related to this and equally significant are the limited investments from government (Tall *et al*, 2021), poor service delivery (Van Antwerpen and Ferreira, 2016), lack of transparency, corruption, and mismanagement of climate finances (Jacobson and Tropp, 2010), all of which pose a serious threat, particularly to marginal communities. Furthermore, the implementation and scaling-up of climate change adaptation interventions are significantly impacted by the politics of climate change (Erikseni *et al*, 2011). 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.

Hence the WEF nexus approach is critically important in bringing together relevant stakeholders to address Sustainable Development Goals (SDGs) and facilitation of cooperative governance towards climate change adaptation planning. The WEF nexus accomplishes this by: (i) improving resource allocation and planning effectiveness (Mpandeli *et al*, 2018); (ii) establishing quantitative relationships among interconnected resources (Naidoo *et al*, 2021); and (iii) identifying priority areas for intervention (Nhamo *et al*, 2020). It also promotes transition and transformation among sectors and stakeholders (Howarth and Monasterolo, 2016). As a result, this study aimed to undertake a pragmatic approach that is based on geospatial analytical methods to support the sustainable implementation of the WEF nexus climate change adaptation interventions in South Africa's Mpumalanga Province.

The present study used the province of Mpumalanga as a case study since it has been suggested to be a hub for South Africa's WEF nexus (Simpson *et al*, 2019). Within the Province, the dominant development paradigm is to blame for the competition between coal mining and agriculture over the use of land and water (Simpson *et al*, 2019). This compromises the water security of the province as both rivals rely on water to operate

efficiently (Ololade *et al*, 2017). Land resources in the province have historically been managed to accomplish a solo purpose of food, energy, or water, which often leads to competing land use objectives (Davies, 2014). This resource trilemma will 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). The current adaptation strategies in this region are impacted by the sectoral framework used for planning and development (Mpandeli *et al*, 2018), which lacks consideration for trade-offs. In a nutshell, cross-sectoral interactions are not sufficiently taken into consideration or coordinated. This happens even among the obviously interrelated climate-sensitive sectors such as water, energy and food. Therefore, in this instance, it is imperative to underline the need for innovative adaptation strategies that encourage sustainable use of water, energy, and food.

Leveraging geospatial data to facilitate planning and implementation of climate change adaptation projects and programmes can improve policy coherence (Casian and Cropvoets, 2023). This is because the WEF nexus approach powered by geospatial information will promote informed planning and implementation methods. Geospatial data provide useful insights for well-informed decisions, fostering positive adaptation outcomes when integrated with different data, methodologies and technologies like statistical and machine learning models and web platforms (Eniolorunda, 2014; Sirmacek and Vinuesa, 2022). Geospatial techniques and machine learning applications allow the development of novel methodologies that estimate and forecast desired results while assessing the degree of uncertainty in these predictions and estimations (Holloway and Mengerson, 2018). Advances in space information science and computer applications have made remote sensing and statistical machine learning applications powerful tools for analysing nonlinear relationships and variable interactions, providing future scenarios and informant decision-making processes (Ryo and Rillig, 2017). Geographical Information Systems (GIS) and remote sensing are the best instruments for enabling up-to-date environmental data acquisition because of their benefits in terms of cost and time savings, as well as their capacity to collect data in remote regions (Ndou, 2016).

Therefore, the current chapter explored the capabilities of geospatial methods and statistical machine learning in supporting the sustainable implementation of the WEF nexus climate

change adaptation interventions. Towards achieving the results, the current chapter was propelled by the following objectives: (1) to compare LULC change results and extreme climatic variables with existing or completed climate change adaptation projects, (2) to determine areas with hotspots and coldspots for climate change adaptation interventions, (3) to analyse complementarity between climate change adaptation interventions and environmental and socioeconomic drivers and (4) to highlight areas where WEF related adaptation interventions should be prioritized.

### 5.3 MATERIALS AND METHODS

This chapter details study methods and their implementation to achieve objectives. The current study employed geospatial and statistical machine learning methods to develop a framework or model that integrates the WEF nexus and climate change adaptation for strategic planning and implementation of adaptation interventions. A schematic diagram showing the methodology used in the present study is shown in Figure 5.1.

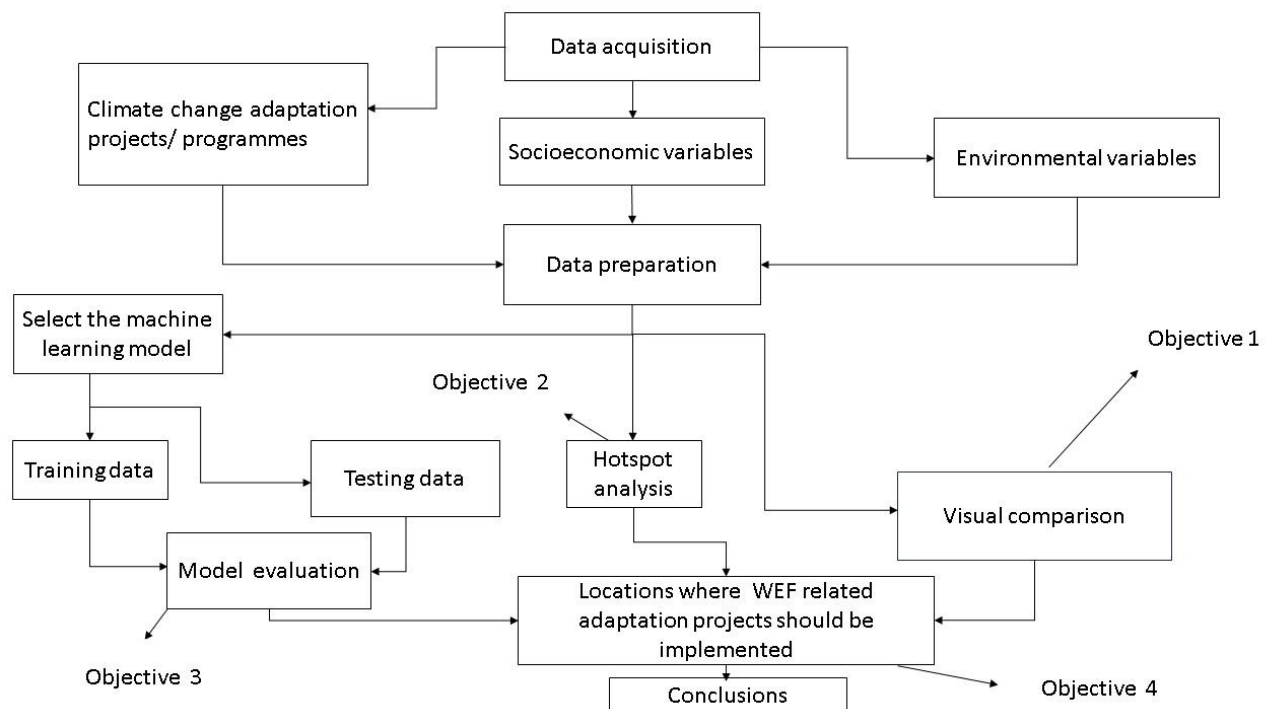


Figure 5.1: Methodological framework of the study.

### 5.3.1 Study area

Mpumalanga Province historically known as Eastern Transvaal is in the northeastern region of South Africa. It is bordered to the north by the province of Limpopo, to the east by Mozambique and Swaziland, to the south by the provinces of KwaZulu-Natal and Free State, and to the west by the province of Gauteng. The province is divided into 3 district municipalities, which can be seen in Figure 5.2. These are further divided into 18 local municipalities. The provincial capital is Mbombela. The Transvaal Drakensberg divides the province into an interior plateau or Highveld and a subtropical Lowveld (Esterhuysen and Smith, 2007). The Mpumalanga Province is home to a wealth of natural resources that have long been used and exploited by humans (Esterhuysen and Smith, 2007). Among these resources are energy minerals, precious metals, non-ferrous and base metals, precious stones, various industrial minerals, and ferrous and related metals.

About 77% of South Africa's prime energy needs are served by coal mining industry (Akinlabi *et al*, 2019), with 70% of it produced in Mpumalanga (Mathu and Chinomona, 2013). A concern for the province's food security is that 61,3% of its land is subject to mining rights (Solomons, 2016). This is because the province is home to over half of the country's high-potential arable land (BFAP, 2012). Concerns over the availability and quality of water for mining, agriculture, and energy production are also getting worse in this province. Despite having one of the fastest-growing economies in Africa (Tyler *et al*, 2021), Mpumalanga Province nevertheless has inequality and poverty (Niyimbanira, 2017). In Mpumalanga, agriculture continues to play an important part in creating jobs and ensuring food security. This province has experienced the effects of climate change, and its economy is dependent on climate-sensitive sectors. The province features two distinct climatic zones: the Highveld, which has hot, humid summers and frigid winters with little to no rain, and the Lowveld, which has mild winters with a subtropical climate. Extreme climatic events in Mpumalanga impact societal and conservation areas (Milan *et al*, 2018).

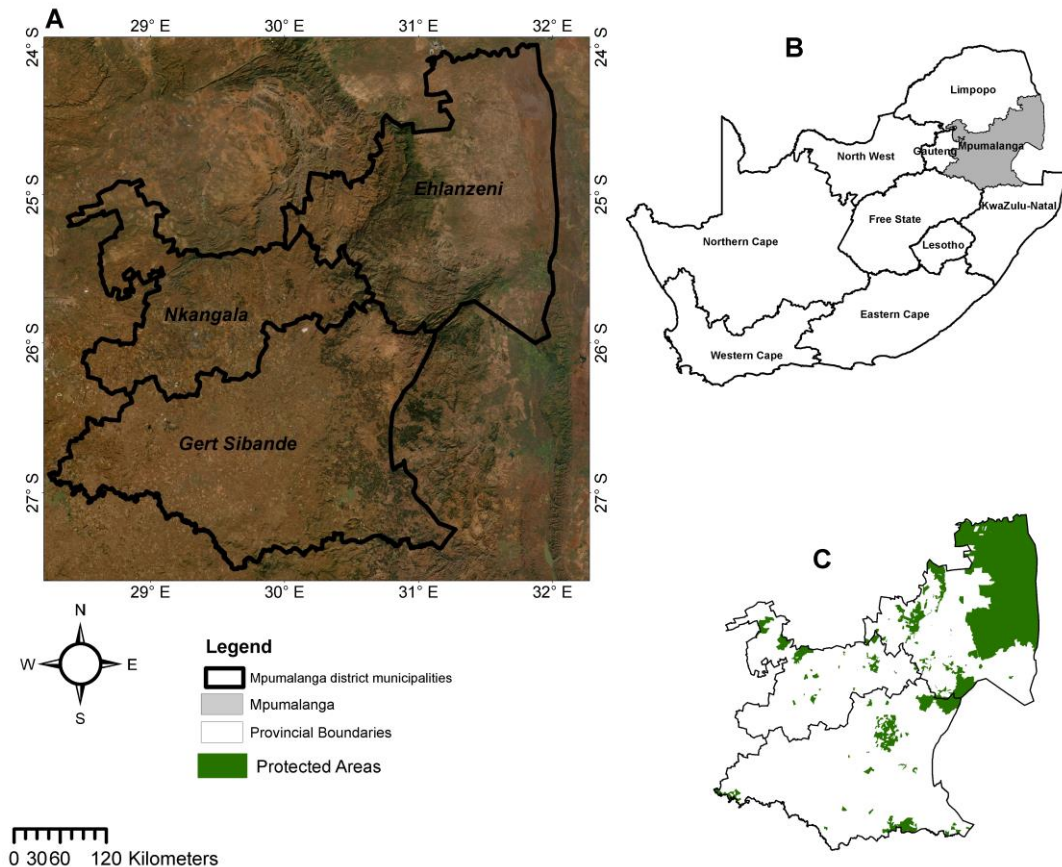


Figure 5.2: Location of the study area. (A) Locality map of the Mpumalanga Province. (B) Mpumalanga Province relative to other provinces in South Africa. (C) Protected areas in Mpumalanga Province.

### 5.3.2 Data acquisition

#### 5.3.2.1 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 Department of Forestry, Fisheries and the Environment (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. Most 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. The study further generated another 131 random points on ArcMap 10.4.1. Subsequently, there were 262 points.

### 5.3.2.2 Acquisition and definition of variables

This section focuses on drivers of the location of climate change adaptation interventions. It is important to examine various factors influencing the adoption of climate change adaptation strategies. Adoption of climate change adaptation strategies is determined by different socioeconomic and environmental variables. Hence, a comprehensive understanding of socioeconomic and environmental vulnerabilities is essential for strategic planning and the implementation climate change adaptation interventions (de Nijs *et al*, 2014). From the environmental point of view, a local adaptation plan would be considered successful when difficulties brought on by climate change for various operations in the sectors are managed. On other side, effective adaptation plans depend on the capacity of stakeholders to engage from a socioeconomic perspective (Vos, 2010). The data was collected based on the actual conditions in the Mpumalanga Province, available data and previous climate change adaptation related studies in the region.

#### (i) Environmental and extreme climatic variables

The environmental variables used in this study included topographic factors, extreme climatic variables, LULC change results and soil properties. This section will discuss the environmental variables and their acquisition process by which they are argued to influence the adoption of climate change adaptation interventions. The results of global climate change models show that the effects of climate change may be extremely severe at high elevations and in areas with complex topography (Dixit, 2011). Therefore, topographic information is important for assessing climate change exposure. Lu *et al* (2020) agreed that there is a need to quantify the topographic influence while preparing for climate change adaptation. The topographic measures used in the present study were derived from the Digital Elevation Model (DEM) of a 30-meter spatial resolution. The DEM was acquired from United States Geological Survey (USGS, <https://earthexplorer.usgs.gov/> accessed on the 12 July 2022).

It has become important to understand LULC change patterns in order to assign land use categories to appropriate locations while taking the effects of climate change into consideration. The study used LULC change information derived from the South African National Land Cover (SANLC) data repository for 1990 and 2020 datasets. The SANLC datasets were acquired from Department of forestry, fisheries and the environment (DFFE) ([https://egis.environment.gov.za/data\\_egis/data\\_download/current](https://egis.environment.gov.za/data_egis/data_download/current), accessed on the 12 July 2022). Soil is increasingly important for modern human societies to meet the global demand for food and fiber, especially when considering 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. Soil properties with 250-meter spatial resolution were acquired from SOILGRIDS (<https://soilgrids.org>, accessed on the 12 July 2022).

Dynamic downscaled regional model outputs were used to describe the dry and wet extremes and are determined using daily maximum temperature and precipitation. The analysis of climate extremes over Mpumalanga with reference to 1.5°C projection gives a perspective of climate change associated impacts considered under the Paris Agreement. Here 2 of the 27 extreme climate event indicators suggested by the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indicators (ETCCDI) were used to provide model evidence of climate change over Mpumalanga Province. The dry spell is defined as the “maximum length of dry spell: maximum number of consecutive days with rainfall < 1mm (1961-1990 relative to 2021-2050 period, based on 1.5<sup>0</sup>c projections)”. The wet spell is the “maximum length of wet spell: maximum number of consecutive days with RR ≥ 1mm (1961-1990 relative to 2021-2050 period, based on 1.5<sup>0</sup>C projections). The Council for Scientific and Industrial Research (CSIR) provided extreme climatic data. Further details about this dataset can be accessed in the Green Book (<https://idl-bnc-idrc.dspacedirect.org/server/api/core/bitstreams/17749dda-e9c7-40c0-a7dc-c3786cba0a10/content>).

(ii) **Socioeconomic variables**

Socioeconomic variables must be considered when developing strategies for climate change adaptation, since they affect people's capacity and ability to adapt to the changing climate. They are also important for estimating the effects of climate change on various populations and economic sectors. 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. Most lower income households work in climate-sensitive sectors such as agriculture and fisheries (Zhongming *et al* 2021). Here, the study 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.

### 5.3.3 Preparation of environmental and socioeconomic variables

The 30-meter DEM was used to derive topographic data on elevation, slope and aspect in ArcMap 10.4.1. Soil properties were acquired pre-processed and stored in a Geographic Tagged Image File Format (GEOTIFF). 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 converted from Network Common Data Form (NetCDF) format to raster format. The masking and clipping tools in ArcMap 10.4.1 were used to confine all variables into the spatial extent of the study area. The data information is shown in A.3.1.

#### 5.3.3.1 Framework to classify the land use and land cover classes, and climate change adaptation projects into WEF nexus

The current study classified the LULC classes through the lens of WEF nexus. For example, Water – surface water, dams, irrigation areas, wetlands, water use (water use for various

sectors); energy – mining (coal), fuelwood (woodland cover), energy use by different sectors in the province and food – agricultural activities (commercial, subsistence, crop types, irrigation types and requirements. Only 10 classes from a total of 73 (2020 SANLC data) and 72 (1990 SANLC data) were given priority, and those that are closely related to the WEF nexus. The present study adhered to the criteria set out in Wolde *et al*, (2021), which highlights the LULC types that are directly linked to the WEF nexus. Appendix (A.2.2) shows different LULC categories that are directly linked to the WEF systems.

The adaptation sectors from the NCCRD database were classified into respective WEF groups based on the implemented programme and results of adaptation expected from the programme (A.3.2). This process was done in coordination with the DFFE and provincial personnel. Figure 5.3 is showing the spatial distribution of climate change adaptation projects and programmes targeted on water and food in the Mpumalanga Province.

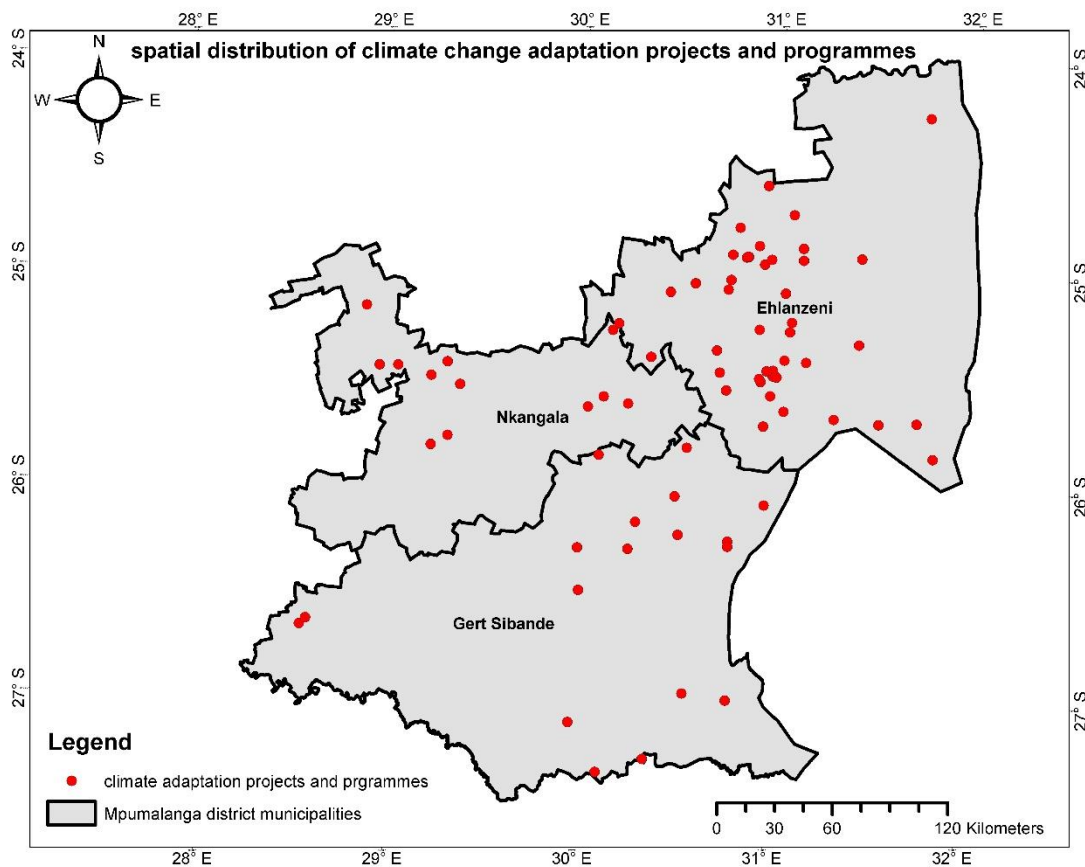


Figure 5.3 spatial distribution of climate change adaptation projects and programmes.

### 5.3.4 Analytical framework

To achieve the aim of this chapter, The study undertook four general steps: (1) comparing LULC change results and extreme climatic variables with existing or completed climate change adaptation projects. (2) assessing areas with hotspots or coldspots of adaptation projects (3) Modelling of the complementarity between the climate change adaptation interventions classified through WEF nexus with socio-economic and environmental drivers (4) highlighting areas that supposed to have adaptation projects related to food or water.

#### 5.3.4.1 Hotspot analysis and LULC change map

Prior to hotspot analysis, the environment setting was carefully chosen, with a folder for storing results. The hotspot analysis was performed in ArcMap10.4.1. Hotspot analysis uses Arc toolbox data management tool. The Integrate tool is the initial step in hotspot analysis, ensuring shared feature boundaries are consistent with x and y tolerances. The x, y tolerance was set to 30 meters. The next step was to collect event data and convert it to weighted point data, in this instance, climate change adaptation interventions were used as an event data. The ArcGIS collect event tool is located beneath the spatial statistics tool and the utilities tool. Following the completion of the Collect event operation, incremental spatial autocorrelation was performed using the analyzing pattern tool set in arc toolbox. Then the data was ready for hotspot analysis. The hotspot analysis is found in the mapping cluster toolset under spatial statistics. Hotspot analysis results were interpolated using Inverse Distance Weighted (IDW) technique to create a raster surface.

For LULC change matrix map, the present study followed methodological approach of previous studies (Bekele and Yirsaw, 2019; Hassan *et al*, 2016; Munthali *et al*, 2019). A Post-Classification Comparison (PCC) method was employed in ArcMap 10.4.1 to detect location and nature of LULC changes by comparing the extent of LULC classes between two periods (1990 and 2020). This technique shows the direction of change or the transition from one point to another (Musetsho *et al*, 2021). The reliability of the PCC is entirely dependent on the accuracy of the initial classifications. The PCC approach used overlay

functions to create LULC change map. More details about this approach are provided in section 3.2 of chapter 3.

#### 5.3.4.2 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 raster datasets at the locations specified in a point feature class. The extracted cell values were stored 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 *et al*, 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 interventions can be explained by socio-economic and environmental variables. This probability technique is based on the interaction of climate change adaptation interventions with socioeconomic and environmental variables in a single spatial unit (pixel).

The 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 scenario 3: combining environmental and socio-economic variables. In the dataset provided, a value of 1 denotes the location of a climate change adaptation intervention, whereas a value of 0 shows its absence. The independent variables in the logistic regression are listed as  $x_1$ ,  $x_2$ ,  $x_3$ , etc., and  $x_n$ . The logistic regression is provided by (3), using the same formular as Lessechen *et al* (2005), Sperandei (2014) and Kindu *et al* (2015):

$$\text{Log} \left( \frac{p}{1-p} \right) = B_o + B_{1x_1} + B_{2x_2} \dots B_{n x_n} \quad (3)$$

The logistic regression uses the log odds of the event in  $\left( \frac{p}{1-p} \right)$ , where  $p$  is the probability of the occurrence, which in this case indicate the location of the climate change adaptation

interventions. As a result,  $P$  is always between 0 and 1.  $B_0$  is the constant.  $B_i$  represents regression coefficients of the reference group and  $x_i$  denotes independent variables.

#### 5.3.4.3 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 the 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 selection approach was used to select independent variables that could account for the location of adaptations. The selected variables were later used in predicting areas that should have climate change adaptation interventions targeted at water/food.

#### 5.3.4.4 Evaluation of logistic regression

Regardless of being a powerful statistical tool, logistic regression should be employed with caution. To ensure the validity of the findings derived using the logistic regression approach, 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 might occur (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 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 summarises the agreement between the observed and fitted values, which might not give information about specific model components (Forero 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. As such, the Receiver Operating Characteristic (ROC) and Area Under Curve (AUC) were used to evaluate the performance of the model. ROC is used to visualise the discriminatory accuracy of the classifiers/predictors (Gajowniczek *et al*, 2014) and AUC provides a prediction of the odds of correctly classifying a randomly chosen object (Polo and Miot, 2020). In addition, the optimal probability was computed to identify cutoff between conditions that are stable and unstable.

## 5.4 RESULTS AND DISCUSSION

This chapter will report results on (1) visual comparison of the LULC change results and extreme climatic variables with existing or completed climate change adaptation projects and programmes; (2) hotspot analysis; (3) Modelling the complementarity between existing or completed climate change adaptation interventions with environmental and socio-economic drivers; (4) highlighting areas where food or water adaptation interventions should be prioritized.

### 5.4.1 Multicollinearity diagnostic results of predictor variables

Variance Inflation Factor (VIF) was employed in this study to diagnose the multicollinearity among the spatial predictor variables. The results are shown in Figure 5.4, Figure 5.5, and Figure 5.6. In scenario 1, which is based on environmental variables only, the two variables were found to be strongly correlated with one another. One of them was removed to prevent multicollinearity. The highest variance inflation factor was 5.13, which is below the threshold of 5 (see Figure 5.4).

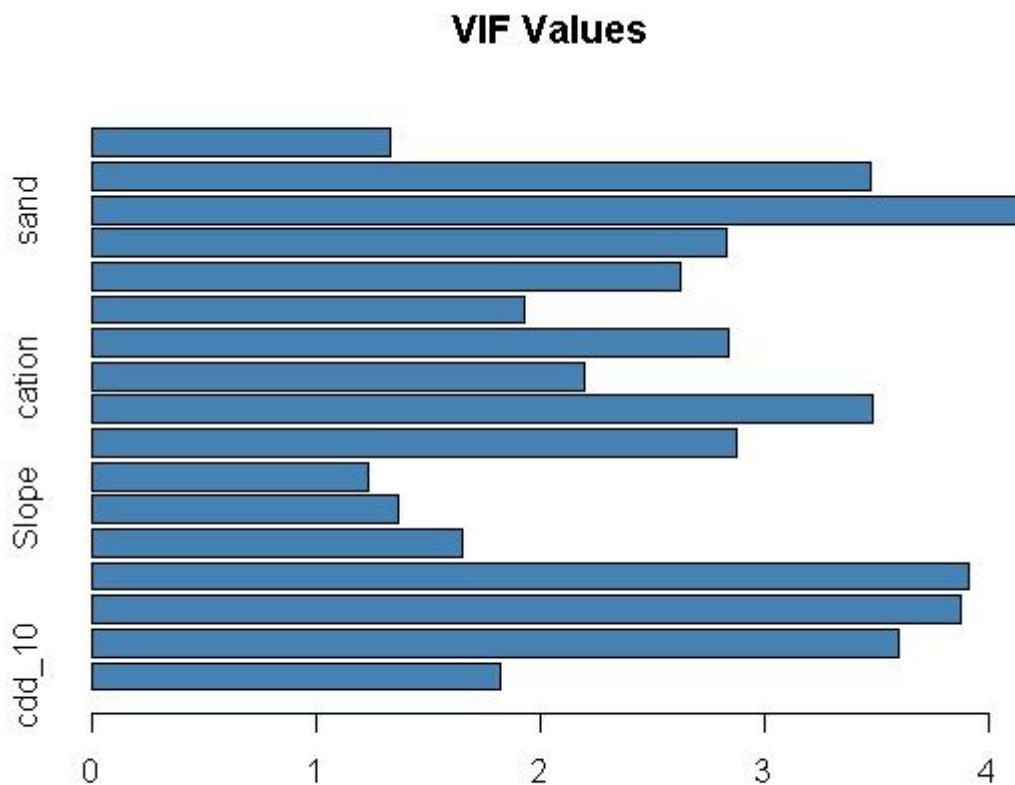


Figure 5.4: multicollinearity diagnosis of predictor variables based on Scenario 1.

The multicollinearity of this model was so severe that only 4 variables were considered for analysis from the total of 49 variables (see Figure 5.5). The selected variables for scenario 2 had a VIF values ranging from 1.17 to 2.05

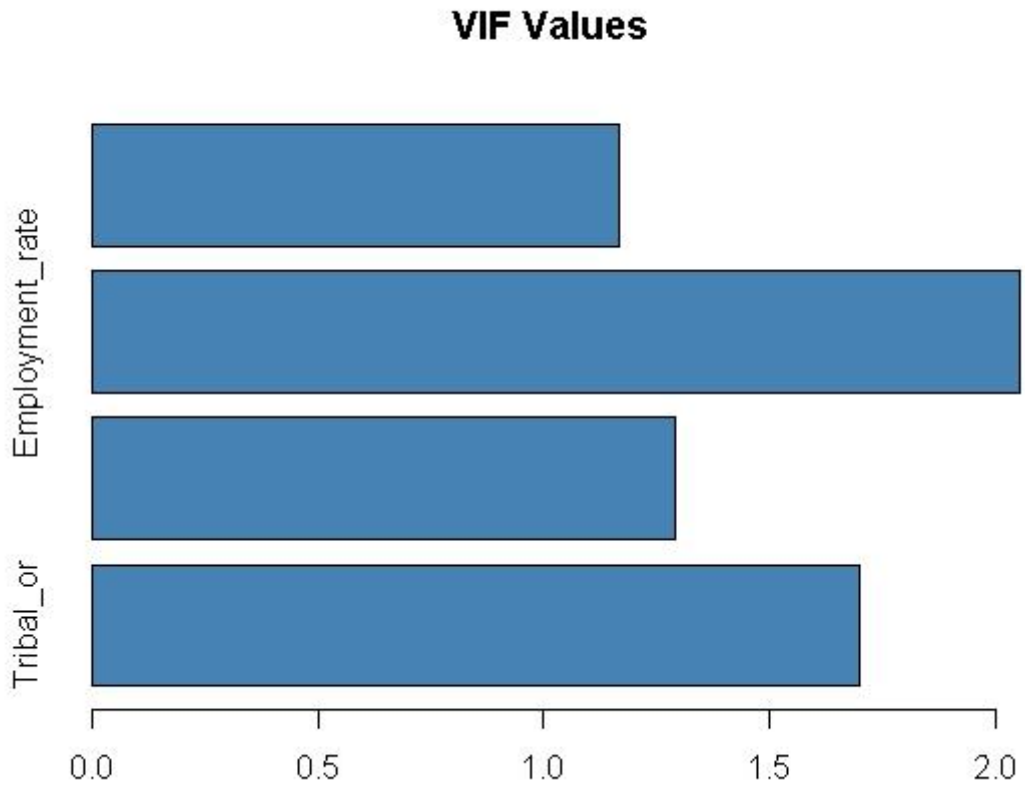


Figure 5.5 multicollinearity diagnosis of predictor variables based on Scenario 2.

The education level categories were strongly correlated with employment status and settlement types. Due to the high level of multicollinearity, only 18 of the 69 total predictor variables were used in scenario 3 (see Figure 5.6).

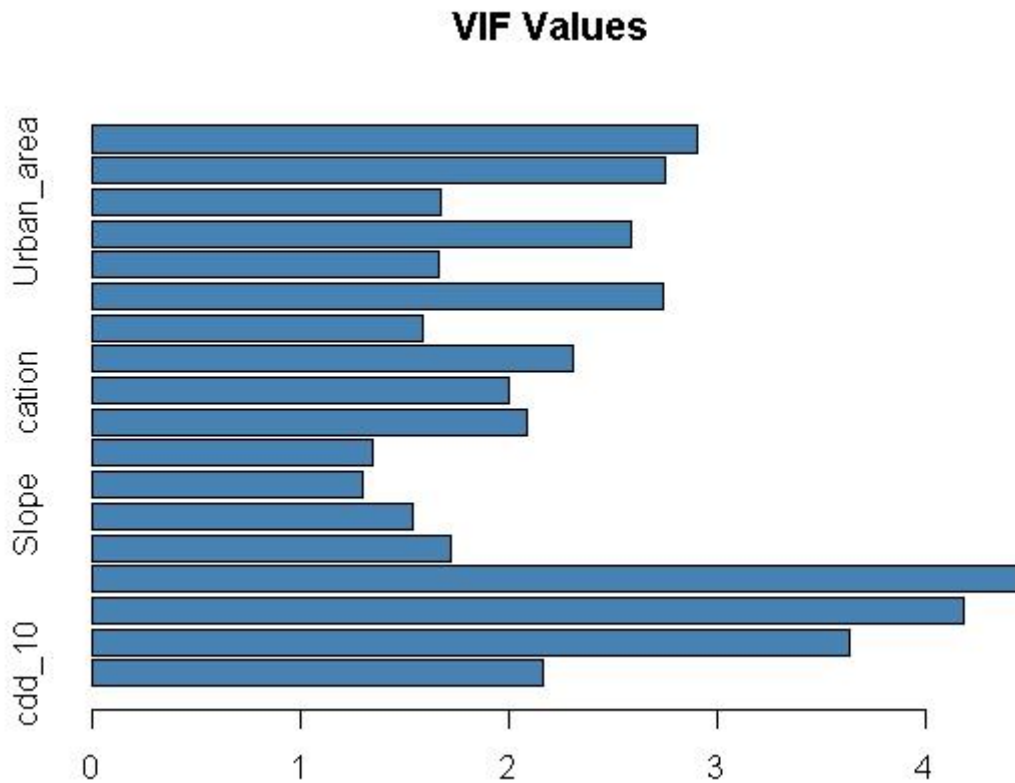


Figure 5.6 multicollinearity diagnosis of predictor variables based on Scenario 3.

#### 5.4.2 Comparison of the LULCC results and extreme climatic variables with existing or completed climate change adaptation projects

In this section, the study will visually compare the complementarity between climate change adaptation interventions to the corresponding land use activities and extreme climatic variables. This is important for evaluating the relevance of the implemented climate change adaptation interventions to associated land use activities and extreme weather events.

##### 5.4.2.1 LULC classified through the lens of WEF nexus vs the location of climate change adaptation projects and programmes

Most of LULC changes, especially those associated with agricultural and coal mining activities, are concentrated in Nkangala (Northwestern region) and Gert Sibande (Southwestern region) districts, but a greater number of climate change adaptation interventions targeted on food and water security is concentrated in the Ehlanzeni

(Northeastern region) district (figure 5.7). The results indicate that there are compromises between land use practices and climate change adaptation interventions in the study area. The study by Olalade *et al* (2017) indicate that the mining and agricultural land use practices are the biggest threats to the province’s water security. 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).

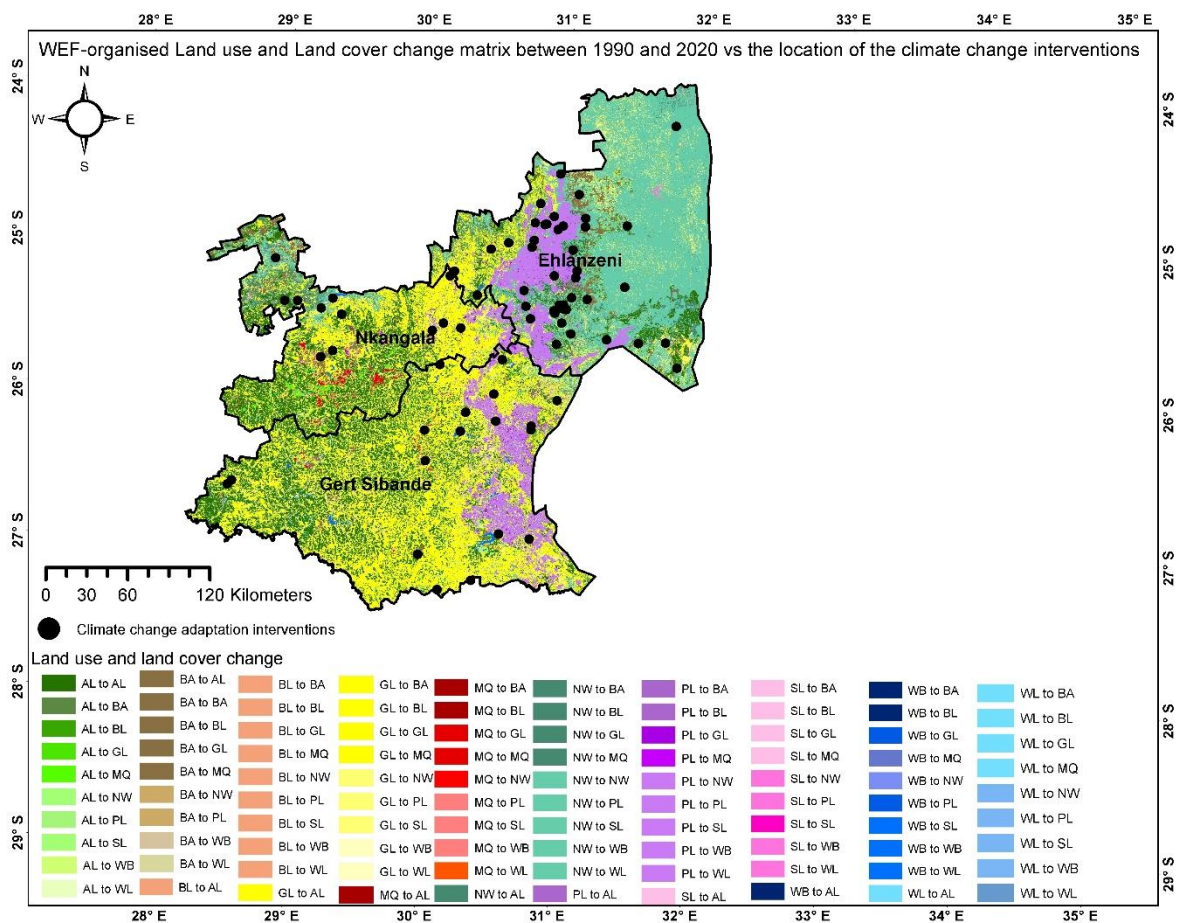


Figure 5.7: Land use and land cover change analysis map, showing the from-to changes of the land use and land cover types of vs spatial distribution of climate change adaptation interventions. AL = Agriculture, BA = Built up areas, BL = Barelands, GL = Grasslands, MQ = Mines and quarries, NW = Natural woodlands, PL = Plantations, SL = Shrublands, WB = Water bodies, WL = Wetlands

**5.4.2.2 Extreme climate variables vs the location of climate change adaptation projects and programmes**

The dry spells (2021-2050, based on 1.5<sup>0</sup>C projections) are evident over a larger part of Nkangala (Northwestern region) and Gert Sibande (Southwestern region) districts (Figure 5.8). Conflicting signs between the 10<sup>th</sup> and 90<sup>th</sup> ensemble percentiles show that the signal of change is less developed over Ehlanzeni district (Northeastern region). Dry spell could some extent indicate the possible intrusion of drought. Mpumalanga Province has a veldfire risk of 70.9%, making it extremely exposed to veldfire hazards (Strydom and Savage, 2016). Therefore, the province needs to respond quickly to the projected increase in consecutive dry days. Most of the climate change adaptation interventions or projects are located in areas of increasing dry spells, which is a positive indicator of complementarity between the underlying environmental change indicators and interventions or adaptation projects (Figure 5.8).

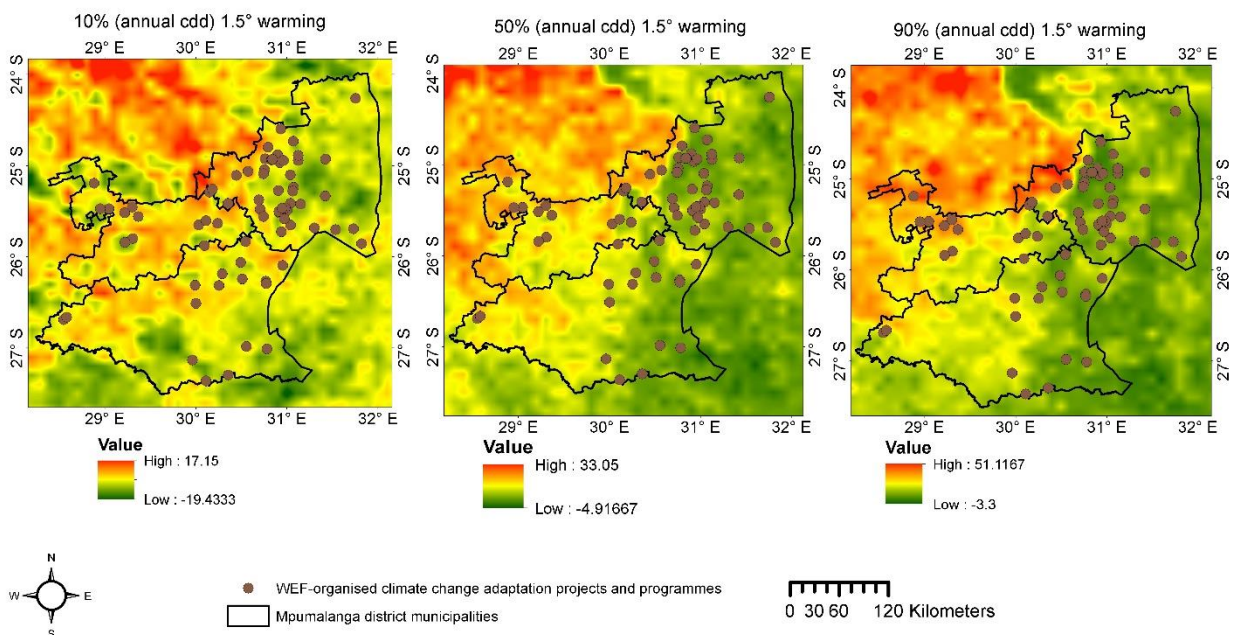


Figure 5.8: Maximum length of dry spell: maximum number of consecutive days with rainfall < 1mm (1961-1990 relative to 2021-2050 period, based on 1.50C projections).

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, with the exception

of south of Kruger National Park (Figure 5.9). Mpumalanga Province is located in the eastern region of South Africa, near Mozambique, which is expected to experience wetter conditions. Climate change has caused irregular fluctuation in rainfall pattern and flood levels in the Mpumalanga Province (DPWRT, 2015).

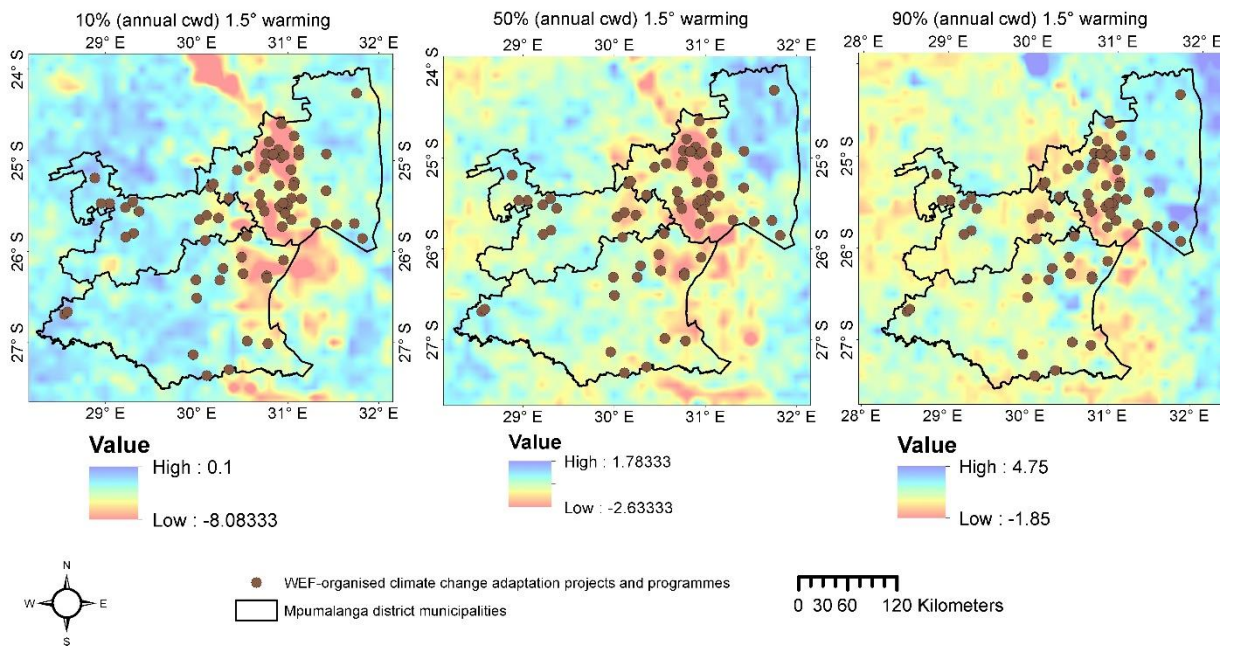


Figure 5.9: Maximum length of wet spell: maximum number of consecutive days with  $RR \geq 1\text{mm}$  (1961-1990 relative to 2021-2050 period, based on 1.50c projections)

### 5.4.3 Analysis of Hotspots: Providing Direction for Action

The spatial distribution of the provincial climate change adaptation interventions or projects varies from local municipality to local municipality depending on the vulnerabilities as well as other socioeconomic or environmental strategies or goals. There are parts of the province with high concentrations of interventions (hotspots), others with low concentrations (coldspots), and areas in the middle with a moderate concentration of interventions. In Mpumalanga Province, 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 5.10). High

concentrations of adaptation interventions have been observed in the Ehlanzeni district municipality (Northeastern region), followed by the Nkangala district municipality (Northwestern region). While Gert Sibande district municipality (Southwestern region) is home to several 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.

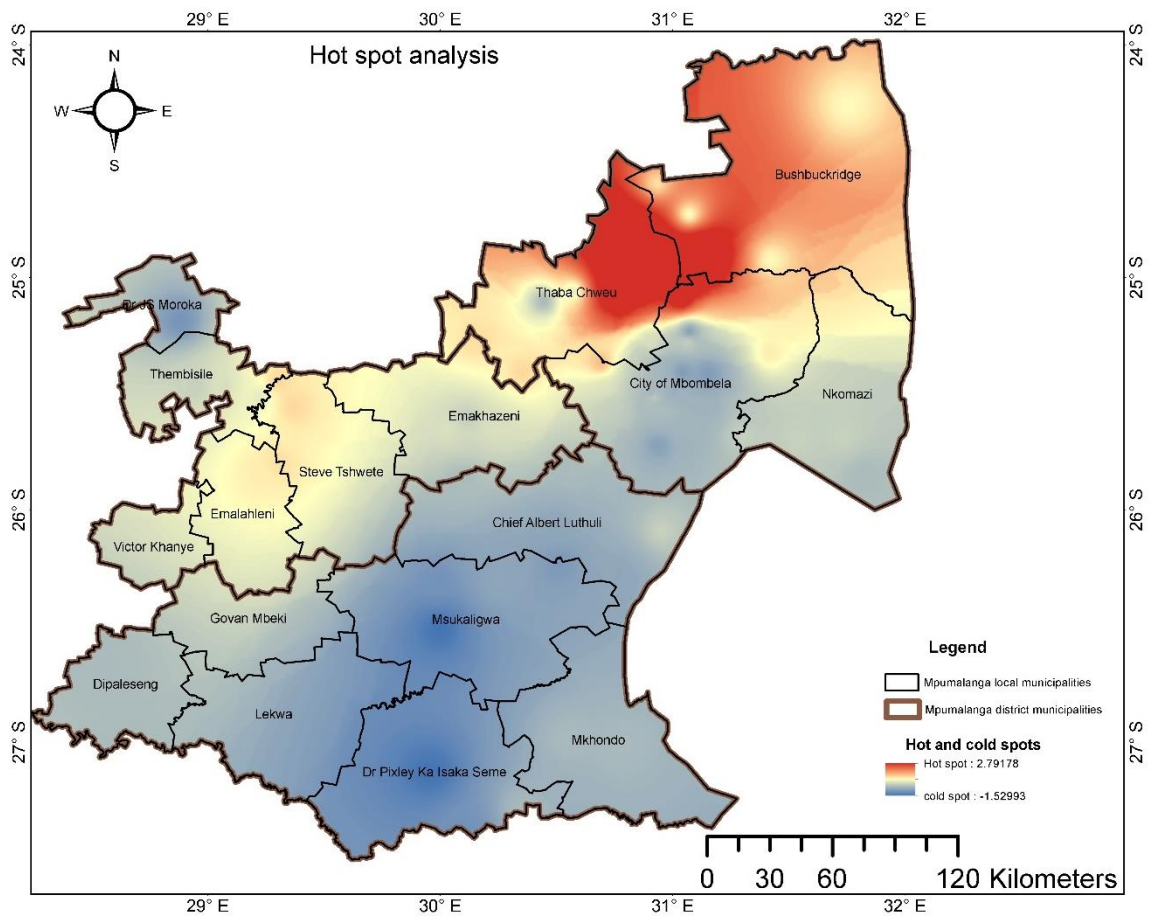


Figure 5.10: Map showing hotspots and coldspots of the Climate change adaptation projects and programmes in Mpumalanga Province.

#### 5.4.4 Modelling the complementarity of climate change adaptation projects or programmes with environmental and socioeconomic variables

### 5.4.4.1 Variables that could explain the location of climate change adaptation projects or interventions

When P-value of the model is below 0.05, it means that the model is statistically significant. This means that all models for the current evaluation were statistically significant. The P-value for model-based scenario 1 is exceptionally low  $2.94 \times 10^{-8}$ , P-value for scenario 2 is  $1.78 \times 10^{-6}$ , which is significant compared to the low P-value. The P-value for the scenario 3 is  $2.98 \times 10^{-3}$ , 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.

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 5.1, Table 5.2 and Table 5.3 shows the variables that can explain the location of the climate change adaptation projects and programmes. The cdd\_10, cwd\_10, pH, aspect, elevation, LULC\_1990, LULC\_2020, tribal or rural and employment rate are statistically significant. This suggests that the adaptation interventions in place target local scale climate risks, stressors, and vulnerabilities.

Table 5.1: 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
elevation	-0.0011952	0.0003913	0.002255 **
LULC_1990	-0.2508189	0.0960525	0.009021 **

LULC_2020	0.2694674	0.0877377	0.002131 **
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Null deviance: 263.06 on 189 degrees of freedom, Residual deviance: 223.85 on 182 degrees of freedom, AIC: 239.85

Table 5.2: 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 5.3: 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_rural	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

Since most of climate change adaptation interventions for water, agriculture, and forestry are carried out through land use or land management (Yoon *et al*, 2019), the statistical significance of LULC changes is a positive indicator of the complementarity between the underlying environmental change indicators and intervention or adaptation projects. These findings also supported earlier assertion of De kort (2020) that aspect appears to be an important driver of adaptive trait divergence in mountainous settlements than elevation. It was further shown that employment rate is statistically significant to the location of adaptation interventions. Understanding the relationship between employment and adaptation is necessary for integrating environmental and social goals. To advance toward sustainable development, economic growth, the creation of jobs, and climate-resilient infrastructure development, it is essential to invest in adaptation (International Labour Organisation, 2018). This shows that adaptation to climate change may result in job growth, reduce job losses, and have other positive effects on the labour market.

The pH of the soil was one of the statistically significant explanatory variables. This result is consistent with the study of Rengel (2011), which noted that soil properties, particularly pH as a master variable that affects all other features of an ecosystem, will be impacted by climate change. The statistical relevance of rural or tribal areas was profound since human settlement is one of the key components of adaptation strategies. This is optimistic because rural or tribal areas are where most mining and agricultural operations are located. While pressing poverty concerns and climate change continue unresolved finding synergies between adaptation and sustainable development is essential for solving global poverty, environmental difficulties, and improving livelihoods and quality of life (Eriksen *et al*, 2011). Therefore, it is imperative to comprehend what it means to successfully adapt to climate change, or what is referred to as “sustainable adaptation”. Sustainable adaptation promotes growth that is both socially and environmentally responsible (Eriksen *et al*, 2011). The result of this study shows that there are significant associations between climate change adaptation and environmental and socioeconomic variables.

**5.4.4.2 model evaluation**

This section focuses on evaluating the model performance. The study accomplished this by measuring the prediction accuracy of the model. Prediction accuracy is the proportion of correctly predicted outcomes in the response class (Wålinder, 2014).

**(i) 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 cutoff 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 5.11). The accuracy of the model decreases just after 0.55 cut-offs. Figure 5.12 shows an erratic trend in the accuracy of the model for different cutoff values ranging from 0.35 to 0.76. It reaches the highest accuracy of 66.41% with the cutoff value of 0.55. Figure 5.13 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.

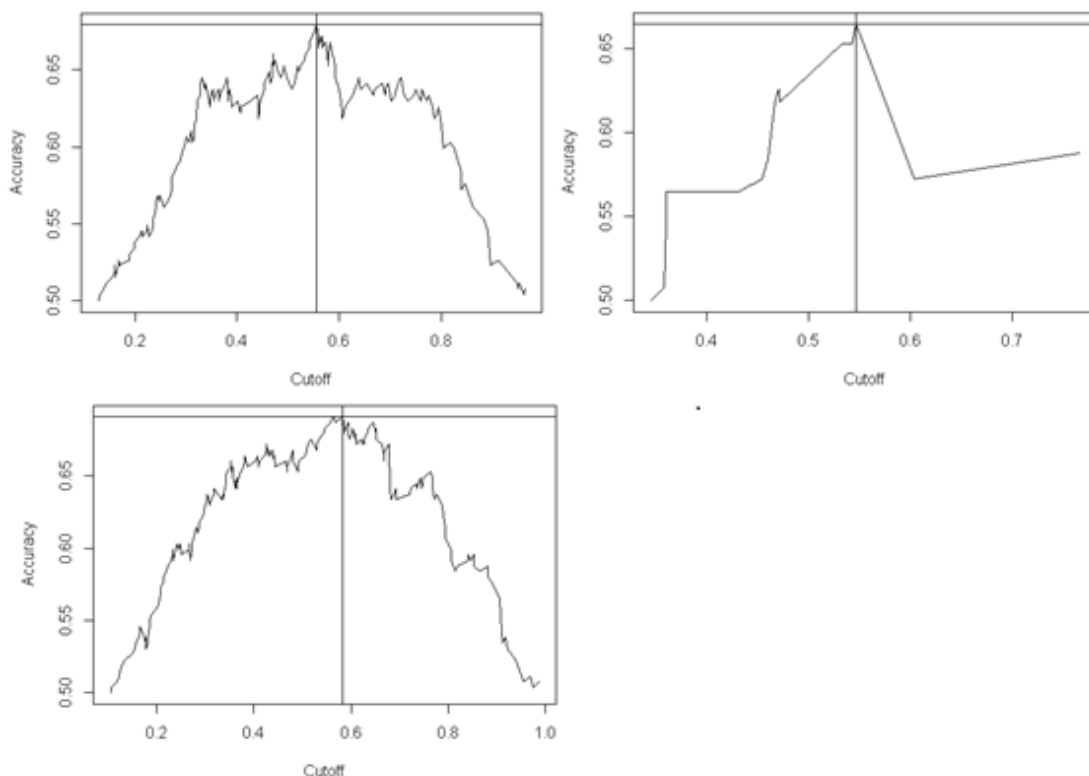


Figure 5.11 (Top Left): accuracy vs probability cutoff (Scenario 1), Figure 5.12 (Top Right): accuracy vs probability cutoff (Scenario 2), Figure 5.13 (Bottom): accuracy vs probability cutoff (Scenario 3).

(ii) **Area under the curve**

The study used the ROC and The AUC to further evaluate the performance of the model. The higher the AUC, the better the performance of the model at distinguishing between the positive and negative classes (Hajian-Tilaki, 2013). When  $0.5 < \text{AUC} < 1$ , there is a high chance that the classifier will be able to distinguish the positive class values from the negative class values. When  $\text{AUC} = 0.5$ , 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 class and 1 class. The models for 3 scenarios have a success rate of more than 60%, showing that all models can properly discriminate between negative and positive classes.

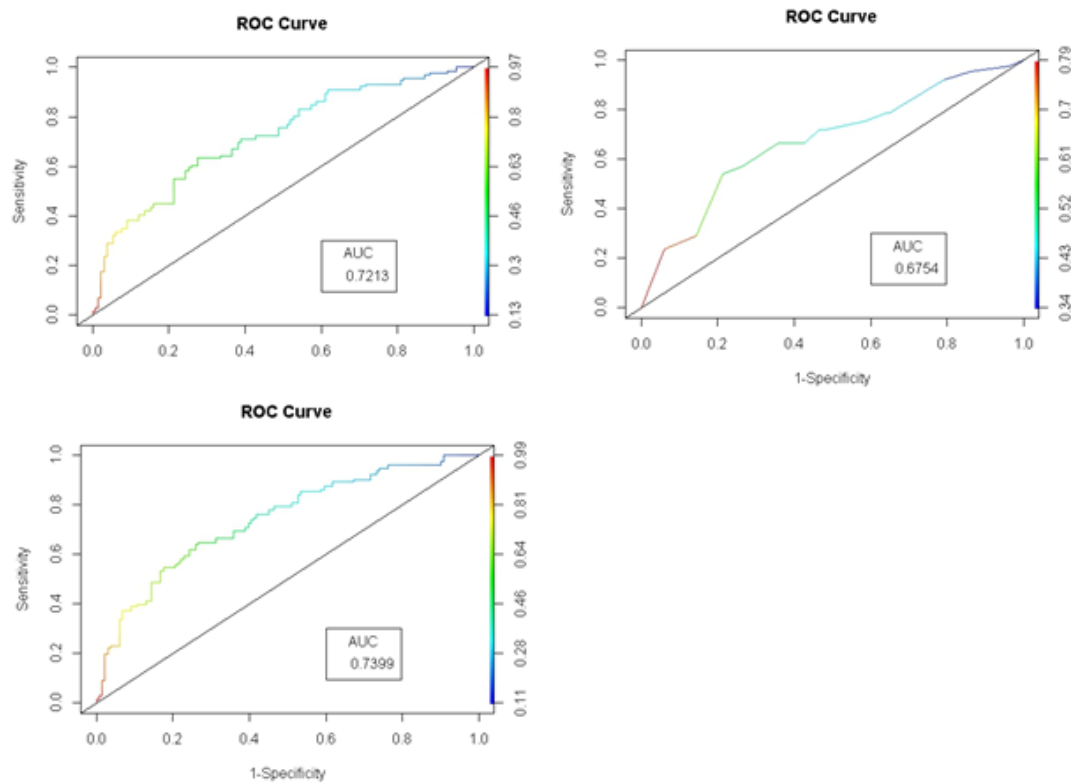


Figure 5.14 (Top Left): The ROC curve of the logistic regression based on scenario 1, Figure 5.15 (Top Right): Scenario 2 and Figure 5.16 (Bottom): Scenario 3.

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### 5.4.5 Suitable locations for water or food related projects and programmes

The spatial estimation map shows the areas where water or food related adaptation projects should be implemented (Figure 5.7). The results of the spatial estimation show that the northeastern region and northwestern of the Mpumalanga Province should be prioritized for adaptation interventions. The areas where adaptation interventions are advisable but not urgently needed were noted in Gert Sibande district municipality (Southwestern region). These results are intriguing because the rapid expansion of coal mining areas in Nkangala district municipality (Northwestern region) poses serious threats to agricultural and water resources.

The analysis of extreme weather events associated with climate change in section 4.3.2.2 showed the projected increase of consecutive dry days over Northeastern and Northwestern regions of the province. A dry spell could be a sign of potential drought encroachment. Water and food security are eventually at serious risk due to the uncertainties around future water supply brought on by climate change. Implementing appropriate and sustainable adaptation interventions is therefore important for lessening the impacts of climate change and enhancing the capacity of Mpumalanga Province to supply water in the future. This also implies that a WEF nexus could be an effective strategy to address the environmental and socioeconomic problems brought on by resource-intensive economic activities and the ensuing climate change. The spatial mapping shows the effect of coarse resolution of soil data and climate model outputs (Figure 5.7). Future modeling research should evaluate the potential impacts of predictor spatial resolution on certain spatial distributions and model performance indicators (Abdulwahab *et al.*, 2002).

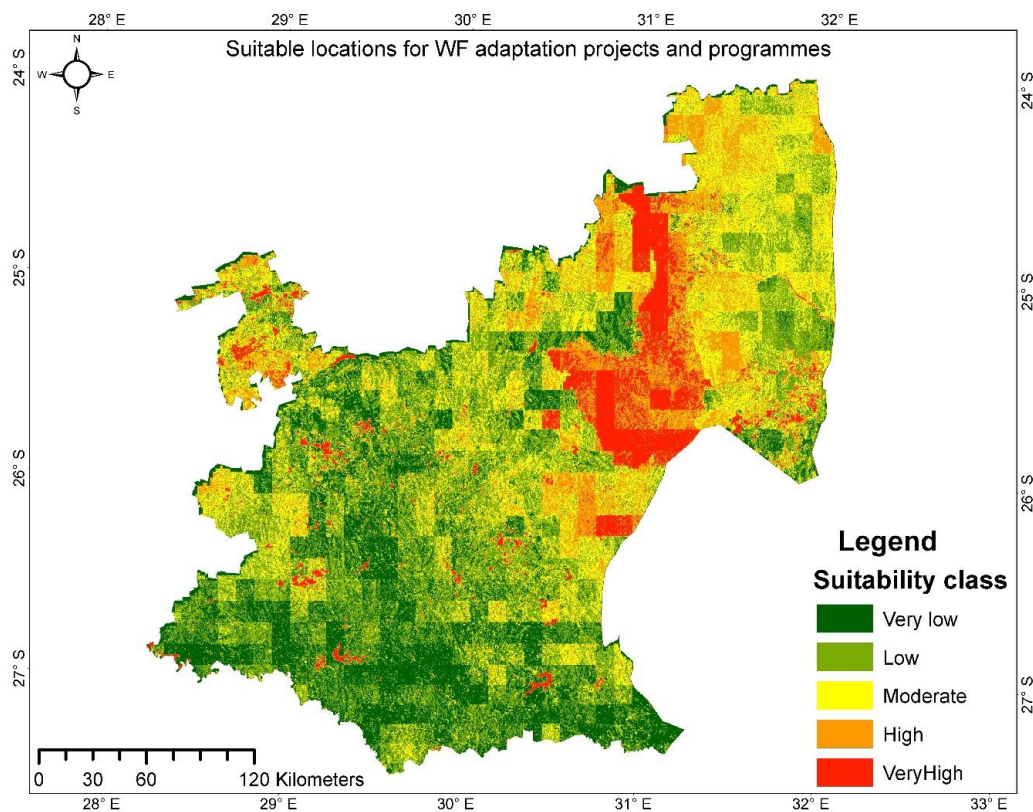


Figure 5.17 Suitable locations for water or food related projects and programmes.

#### 5.4.6 Implications for practice and policy & suggestions for future research

The WEF nexus concept has been recognised as an ambitious and promising strategy for making adaptation decisions to combat the effects of climate change without abandoning the need for sustainable development. It has become one of the main policy and research priorities of the present time. However, there are still gaps that hinder the coordination of research, policy, and practice. In South Africa, WEF nexus is not included in water, energy or food policies. This is because policies on water, energy and food are led by different national departments which do not necessarily communicate with each other on strategic approaches. Furthermore, the findings of this work revealed that climate change adaptation interventions were not directly linked to the associated LULC changes.

This suggests that climate change adaptation interventions must be included into the WEF nexus to ensure adequate resource coordination, harmonization of operations across all

sectors, enhanced resilience, and reduced vulnerabilities (Mpandeli *et al*, 2018). The planning of local implementation initiatives at the provincial level should take local challenges, resources, and capacity into consideration. The statistically significant association of water and food adaptation interventions with some of the environmental and socioeconomic variables implies that WEF nexus planning can help to establish strategies for sustainable and balanced environmental equality and social integrity. Future policy should prioritize informed and least-regret approaches to natural resource usage, which are expressly shaped by a clear understanding of trade-offs. This work needs to be expanded to national level. This can help to improve Communication between relevant national government departments responsible for policies of these natural resources. South Africa need to develop a policy on WEF nexus that unpack the transition in between research-policy-practice. Also, a champion is needed to drive WEF nexus platform into areas of political and social influence.

## 5.5 CONCLUSION

The study was carried out in the South African province of Mpumalanga, with the aim of finding a practical governance framework that supports the sustainable implementation of the WEF nexus-adaptation interventions. Mpumalanga Province is rich in climate-sensitive resources, and the way these resources are administered often results in compromises. This is mainly because policies on water, energy and food are led by different national departments which do not necessarily communicate with each other on strategic approaches. Similar shortcomings have been noted in the current adaptation strategies in this region, which are moulded by sectoral framing. The study provided an opportunity to show how earth observation data and geospatial analytical methods can be applied to support integrated management of vital natural resources that are essential to human welfare and the pursuit of SDG targets and goals related to climate change adaptation. This was a unique study because it was able to integrate earth observation data and other data into models to explore the connection between land use activities and implementation of climate change adaptation interventions in the WEF nexus sectors. The conclusion of this chapter will be written in accordance with its objectives

The first objective 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 clear that areas with extreme climatic variables (such as those related to drought) were linked to a higher number of interventions. Although there were changes in LULC, these were not directly linked to actions for climate change adaptation. The second objective focused on determining the areas with hotspots and coldspots for climate change adaptation interventions in the study area. High concentrations of adaptation-related interventions have been observed in the Ehlanzeni district municipality, followed by the Nkangala district municipality. The coldspots were observed in Gert Sibande district municipality (Southwestern region).

The third objective was to analyse complementarity between climate change adaptation interventions and environmental and socioeconomic drivers. The cdd<sub>10</sub>, cwd<sub>10</sub>, pH, aspect, elevation, LULC<sub>1990</sub>, LULC<sub>2020</sub>, tribal or rural and employment rate are statistically significant to climate change adaptation. The last objective of the study was to identify areas where WEF related adaptation projects should be prioritized. The results of the spatial estimation revealed that the northeastern region and northwestern region of the Mpumalanga Province should be prioritized for adaptation interventions.

## CHAPTER 6                      SUMMARY,                      CONCLUSION                      AND RECOMENDATIONS

### 6.1 SUMMARY OF KEY FINDINGS

The Mpumalanga Province, the second smallest province in South Africa is richly endowed with natural resources that are vital for water, energy and food. These resources are necessary for livelihoods, economic development and biodiversity. The demand for land increases with population growth and economic development, leading to an increase in a variety of land use activities. This has caused coal mining and agricultural production in the province to compete for the use of land and water. Mpumalanga Province has experienced significant LULC modifications, much like any other province in South Africa endowed with an abundance of natural resources. However, during the past 30 years, these changes have taken place at an unprecedented rate.

The present study investigated LULC change dynamics of Mpumalanga Province from 1990 to 2020, their impact on WEF nexus resources and implications for future adaptation strategies. A further analysis was done to understand the drivers of the climate change adaptation interventions. Using the understanding of the drivers and advanced statistical analysis, a framework or model was developed to synthesize and prioritize potential areas of climate change adaptation intervention or action in Mpumalanga Province. To achieve these objectives, the study adapted an integration of geospatial and statistical machine learning techniques. These tools have been used by many authors that are running similar studies.

Remote sensing provides key information for monitoring the global environmental properties of the Earth. LULC change information derived from Remote sensing data helps to understand environmental change process and highlight areas that require

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intervention. LULC change is an important spatial input data for several modeling studies. The LULC changes pose a serious threat to the resources of food, energy and water required for sustainable development. The generated datasets from this study provided timely, up-to-date, and accurate LULC change, allowing efficient and sustainable natural resource management. The LULC change were analyzed through the lens of WEF nexus. Understanding LULC changes and estimating their effects on WEF nexus resources will provide government decision-makers with a scientific foundation to improve the current land development and planning policies.

It is evident that LULC changes occurred in the last 30 years in the Mpumalanga Province. The results show that the major LULC changes in the Mpumalanga Province are related to mining, agriculture, grasslands, woodlands, and built-up areas. For example, agriculture (18.84% to 23.73%), mines and quarries (0.61% to 0.79%) and built-up areas (2.33% to 3.41%) substantially increased while grasslands (37.36% to 30.39%) and shrublands (1.09% to 0%) drastically declined between 1990 and 2020 in the study area. The LULC maps generated for 1990, 2014, 2018 and 2020 were derived from the SANLC datasets. Shrublands and barelands experienced the most dramatic change, with 99.99% and 87.12% of their LULC areas changing into other classes, respectively, based to the PCC of the LULC transition matrix (1990–2020). All of these changes have a direct impact on water supplies, energy sources, and food production. The observed LULC changes in the study area suggest that inadequate planning in the public sectors, which overlooks significant nexus elements, could lead to inappropriate resource allocation. Therefore, 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. Systems thinking is required to provide an integrated framework for decision analysis in order to improve decision-making processes and analyse relevant consequences for better information availability about WEF nexus. This will ensure that the scarce environmental resources (water, energy and food) are optimally allocated in a manner that maximises societal benefit.

Regarding shocks, the study found out that Mpumalanga Province is also exposed to extreme weather events particularly flooding and drought. The analysis of climate extremes provided a perspective of climate change associated impacts. As a result of the shock, the study focused on showing the climate change adaptation interventions through the lens of WEF as

updated in the database in relation to LULC change 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 LULC change, they were not associated specifically with climate change adaptation interventions. The most important response to the shocks caused by a lack of understanding of the social, economic, and environmental circumstances prevailing in Mpumalanga Province is the strengthening of the cooperative model between the government departments. Such an opportunity can be provided by the WEF nexus.

The study also highlighted the importance of integrating environmental and socioeconomic knowledge, since it is critical to the strategic planning and the implementation of climate change adaptation projects or programmes. The logistic regression model was used to estimate if the location of climate change adaptation interventions can be explained by socioeconomic and environmental drivers. P-values less than 0.05 indicated statistical significance for the variables. This implies that the location of climate change adaptation interventions could be explained by those variables. The results of this study show that there are significant associations between climate change adaptation interventions and environmental and socio-economic variables. This indicates that the adopted climate change adaptation interventions in the study area are centred around climate risks, stressors, and vulnerabilities. The results showed the potential of statistical machine learning and geospatial methods to provide insights into the complex interactions between adaptation interventions and feedbacks within the socio-economic and environmental systems.

The study used the drivers (environmental, and socio-economic variables) of climate change adaptation and statistical machine learning techniques to develop areas of potential climate change adaptation interventions. This could be used in the systemization of planning and decision-making at provincial level to support sustainable adaptation. The results showed that the northeastern region and northwestern region of the province should be prioritize for interventions target at water and food. The results obtained indicate that the WEF nexus approach, which is based on geospatial modeling, has the potential to promote well-informed planning and implementation strategies.

## 6.2 RESEARCH CONTRIBUTION TO SCIENTIFIC ADVANCEMENT AND SUSTAINABLE CLIMATE CHANGE ADAPTATION

The use of earth observation data and geospatial techniques 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 Department of Science and Innovation (DSI)’s Decadal Plan. The study showed the importance of earth observation data and geospatial techniques in ensuring that the data service created for WEF nexus meet the demands of decision-makers. The study also demonstrates the capacities of geospatial tools for analyzing integrative datasets. The outputs of the study are pragmatic and readily usable for land management decisions.

This study addresses an exceptionally pressing subject in climate change on access to clean water, energy, and nutritious food. The study’s high linkage with important SDGs, particularly SDG 2 (food), 6 (water), and 7 (energy) help to stimulate a critical thinking on aligning the SDGs with planetary boundaries in the post-2015 development agenda. The work integrates the WEF nexus and climate change adaptation to enhance resource coordination, synchronize activities across sectors, improve resilience, and reduce vulnerabilities. This can enhance 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.

This study was very instrumental in the improvement of a national database for Mpumalanga Province, where the adaptation related projects (i.e., completed, current and planned) are being implemented, by whom, at what scale, and at what cost? The DFFE is managing the development process of the NCCRD ([NCCRD \(environment.gov.za\)](http://nccrd.environment.gov.za)); while SAEON is contracted to manage the ‘look and feel’ of the database. The NCCRD facilitate the monitoring and tracking of national, provincial and local responses to climate change (Please see the contribution made by the current study at: <https://nccrd.environment.gov.za/user/submissions>). The contribution of this work will directly impact South Africa’s National Climate Change Adaptation Strategy and the national

discussion around climate change adaptation and the WEF nexus. Furthermore, this will help to ensure that sufficient, reliable, and publicly available data is available to scientists and decision-makers to address WEF nexus-based adaptation challenges, ensuring that the decision-making processes are transparent, robust, and broadly supported.

The ideas and results of this study were shared with several stakeholders through participation in various workshops arranged by WRC and CSIR (held at CSIR International Convention Centre), Mpumalanga Provincial departments (the launch of the COMPACT of Mayors and Administrators in Mpumalanga Province), Tshwane Metropolitan (Climate change research conference hosted by the city of Tshwane and Tshwane University of Technology), and international conference (African Association of Remote Sensing of the Environment international conference held at Kigali, Rwanda). The current study also used ArcGIS pro and ArcGIS online to create a geospatial visualisation tool that complies with emerging trends and directions in geospatial information science for creating, sharing, and interacting with spatial data on the web (please see A.3.3). Furthermore, this allowed the integration of different types of data, such as vector and raster. The geospatial web mapping tool improved data visualization to visualize the products used and derived in this study. It enables the users to change the look and feel of their maps to fit their own needs and tastes.

Ensuring data provision is the main obstacle impeding the WEF nexus. Geospatial web mapping tools increase the accessibility of data by eliminating the need for specialized software or hardware to view or edit the maps. See the geospatial Visualisation tool in appendix (A.3.3). This will facilitate data sharing within the basket of climate adaptation projects for the province of Mpumalanga. This is because geospatial web tools can allow multiple users to work on the same map or project simultaneously. This will also improve communication between entities who collect the WEF data and decision makers who use those data.

### 6.3 LIMITATION OF THE STUDY

The absence of energy-related climate change adaptation projects in the province of Mpumalanga partly hindered the current study, despite its positive results. As such the analysis focused on water and food related climate change adaptation interventions.

### 6.4 RECOMMENDATIONS AND FUTURE RESEARCH

This work 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. However, there are still gaps that need to be addressed in the future. Considering the study's conclusions, the research suggests that:

- Since earth observation data and geospatial techniques provide a consistent supply of spatio-temporal data (including historical data) for evaluating patterns in LULC change and their effects on WEF resources, they ought to be employed as primary investigative tools for WEF nexus assessments. An understanding of the impact of LULC changes on WEF nexus resources can facilitate collaboration and reduce silo operations in WEF resource management.
- The NCCRD would be the primary source of data that facilitates easy access to comprehensive and cogent data about climate change adaptation, updating it should be given top priority. More climate change adaptation interventions for both water and food are still required. However, if a tool is going to take into consideration a whole WEF nexus synthesis, energy ones should be a priority.
- To improve the dependability of the methods used in this study, large-scale and high-spatial-resolution data must be used. This will increase the clarity and level of detail of the results.

- Public sector planning must pay attention to the connection between the planning and implementation of WEF nexus activities and climate change adaptation processes.
- There is scope to upscale the coverage of the analyses done in this study to reach other provinces. The upscaling of this work should aim to cover the whole country. This will promote interactions with different stakeholders and result in the release of data resources.
- The new trends and directions in geospatial information science for creating, sharing, and interacting with spatial data on the web should be incorporated in the WEF space. These geospatial web mapping tools promote easy data sharing among various members.
- It is therefore highly recommended that the methodology employed in this investigation be employed to guide planning processes by those interested in translating the WEF nexus into workable or relevant solutions for climate change adaptation, as the approach is generic and widely applicable.

**CHAPTER 7**

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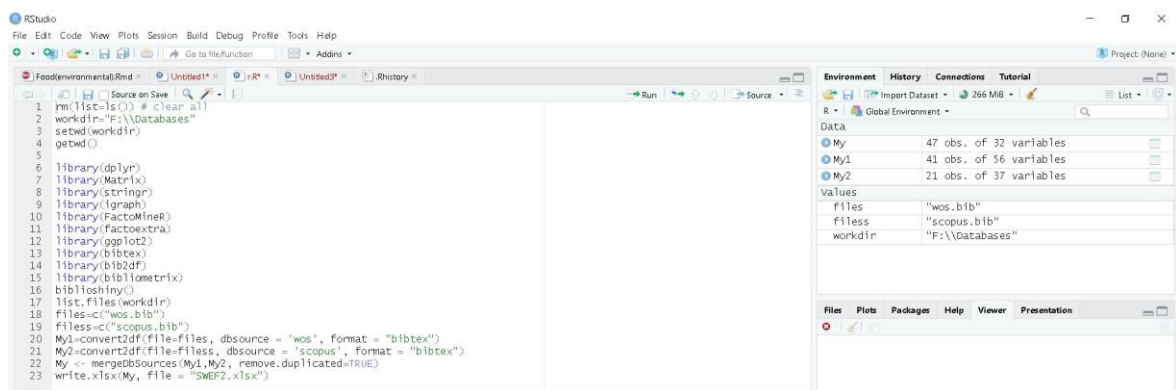
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## CHAPTER 8 APPENDIX A

A.1 chapter 2: A bibliometric review of water-energy-food nexus and climate change adaptation

### A.1.1 Merge the web of science and Scopus and remove duplicates



```

1 rm(list=ls()) # clear all
2 workdir="F:\\Databases"
3 setwd(workdir)
4 getwd()
5
6 library(dplyr)
7 library(Matrix)
8 library(stringr)
9 library(igraph)
10 library(factoMineR)
11 library(factoextra)
12 library(ggplot2)
13 library(bibtex)
14 library(bib2df)
15 library(bibliometrix)
16 biblioshiny()
17 list.files(workdir)
18 files=c("wos.bib")
19 files=c("scopus.bib")
20 My1=convert2df(file=files, dbsource = "wos", format = "bibtex")
21 My2=convert2df(file=files, dbsource = "scopus", format = "bibtex")
22 My <- mergeBBSources(My1,My2, remove.duplicated=TRUE)
23 write.xlsx(My, file = "WEB2.xlsx")

```

A.2 chapter 3: analysis of land use land cover dynamics (1990 – 2020) in Mpumalanga Province, South Africa: implications for WEF nexus

### A.2.1 LULC reclassification based on Thompson's standard land cover classification scheme

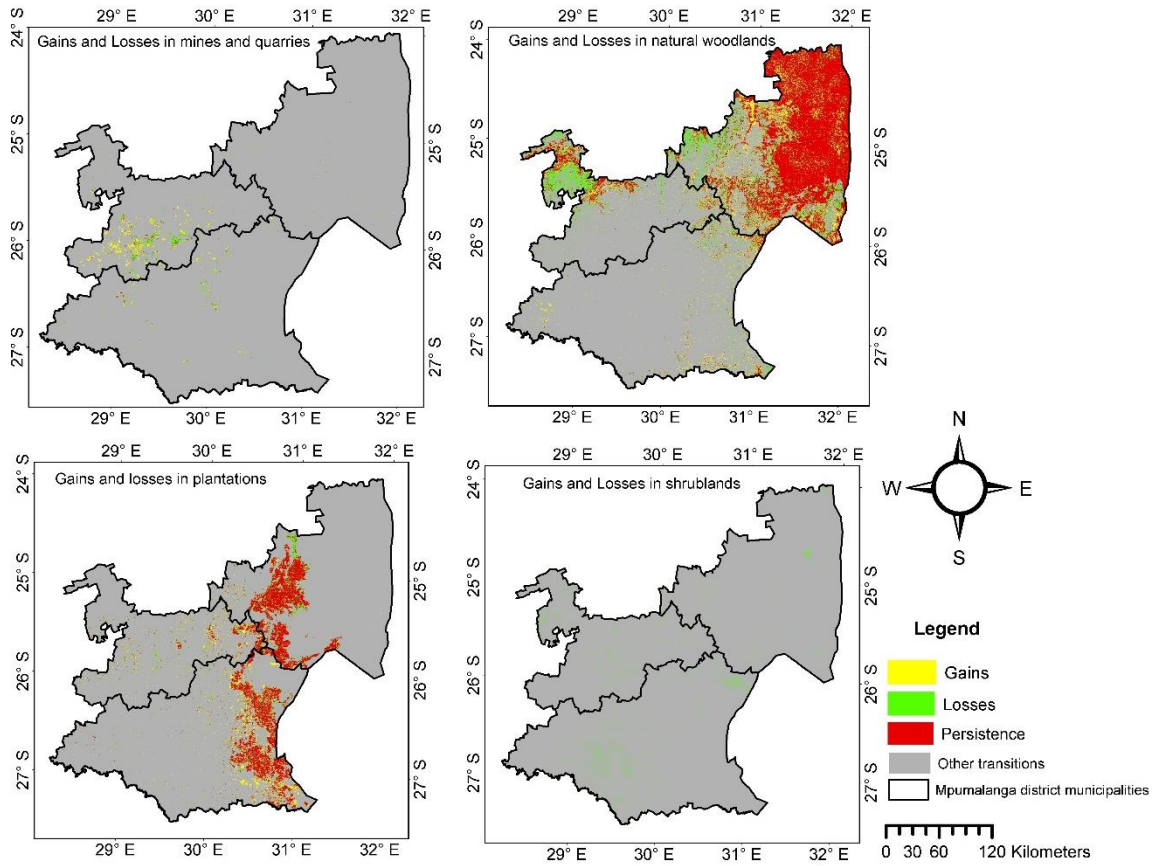
Class Number	Class name	Descriptions
1	Agriculture	Cultivated commercial permanent orchards, cultivated sugarcane pivot irrigated, cultivated sugarcane non-pivot and cultivated emerging farmer sugarcane non-pivot, commercial annual crops pivot irrigated, commercial annual crops pivot irrigated, commercial 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

#### A.2.2 Framework to classify LULC in the lens of WEF nexus

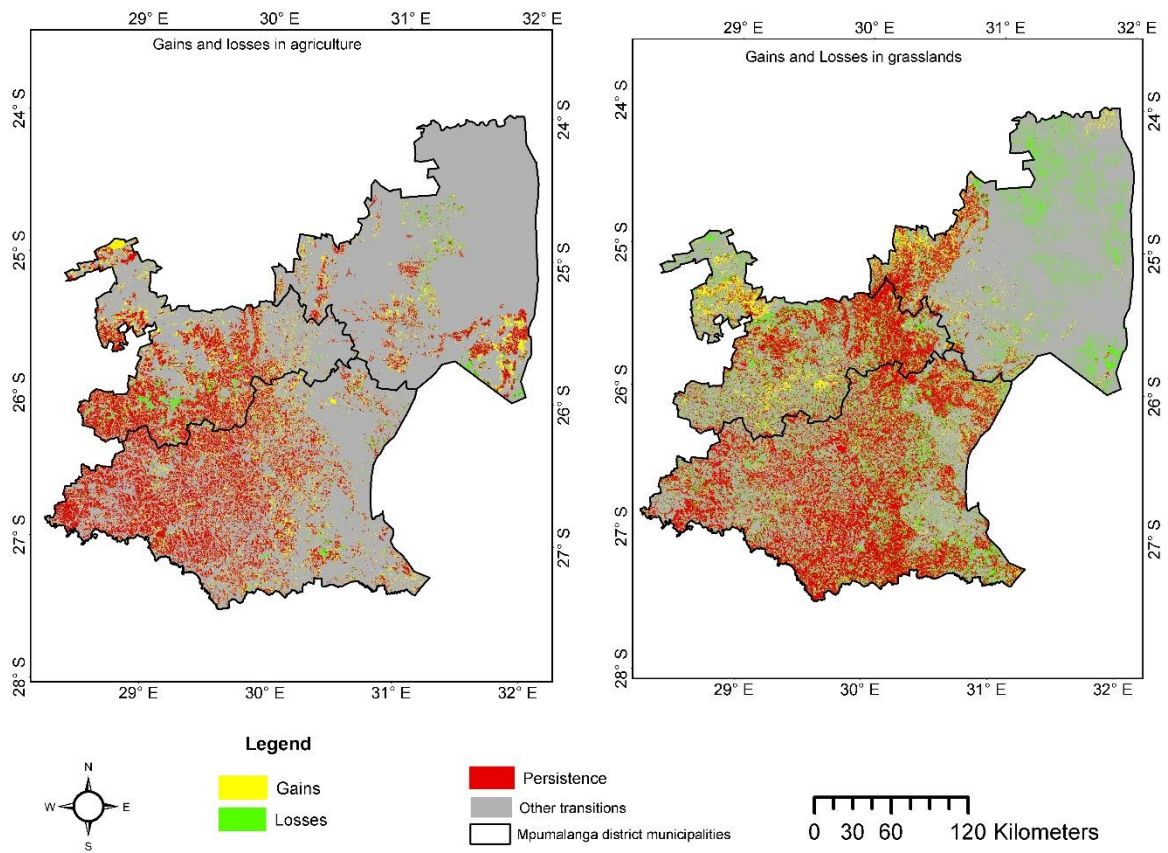
<b>LULC types</b>	<b>Water</b>	<b>Energy</b>	<b>Food</b>
Plantations	Keep some water for crops, reliable supply of clean, fresh water as well as flood and erosion control and climate regulation	Supply woody biomass, sedimentation protection, and biofuel plants	Earnings to support food access and ecological services connected to food security
Bareland	Water conservation, 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
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	Electricity and natural gas are major sources in	Changing dietary tastes and growing food demand

	growing consumption) water pollution and flooding	commercial buildings	
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.

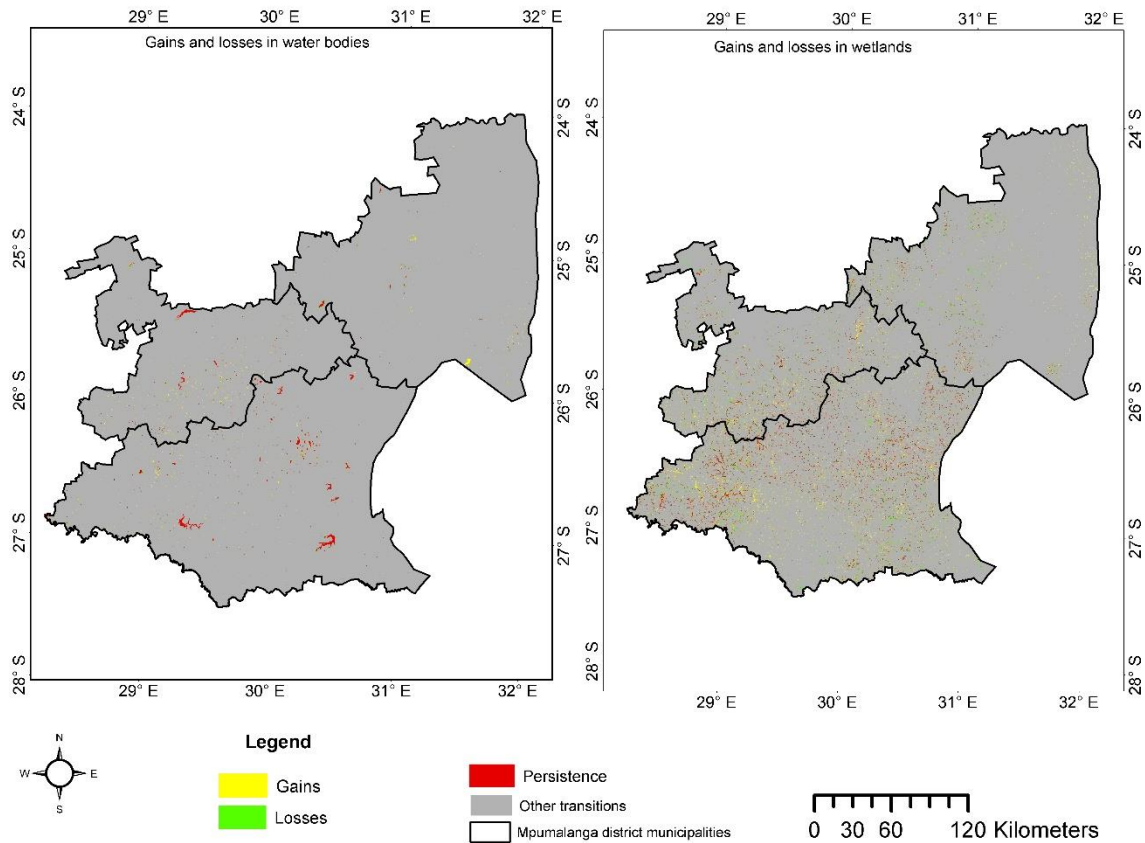
A.2.3 Land use types as a source of energy in the study area



A.2.4 Land use types as source of food in the study area



A.2.5 Land use types as a source of water



### A.3 CHAPTER 4: A GEOSPATIAL FRAMEWORK FOR the sustainable implementation of the Water-Energy-Food NEXUS climate change adaptation interventions

#### A.3.1 Information table

Variable category	Variable Name	Data type
Land use Land cover changes	SANLC data 1990 and 2020	continuous
Climate factors	CDD (10,50,90)	continuous
	CWD (10,50,90)	continuous
Topographic factors	Slope	continuous
	Aspect	continuous
	Elevation	continuous
Soil Characteristics	Bulk density	continuous
	Clay content	continuous
	Coarse fragment	continuous

(Physical soil properties and chemical soil properties)	sand	continuous
	silt	continuous
	cation exchange capacity (at pH7)	continuous
	nitrogen	continuous
	Soil organic carbon	continuous
	pH	continuous
Socioeconomic factors	Population growth	continuous
	Settlement type	continuous
	Income level categories	continuous
	Education level categories	continuous

Cdd = Consecutive Dry Days, Cwd=Consecutive WET Days

A.3.2 Adaptation projects and programmes classified through the lens of WEF nexus 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,	Water and Biodiversity

	siltation, damage to estuaries and diseases, and problems affecting tourism, transport, trade and recreation.	
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 degradation, land use change and farming practices.	Water and agriculture
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 <sub>2</sub> changes, and in turn provide an indication of the levels of vulnerability applicable to	Agriculture (grazing lands)

	specific plant biomes and urban/rural settlements.	
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## CHAPTER 7

## APPENDIX A

## A.3.3 Link to the geospatial visualization tool

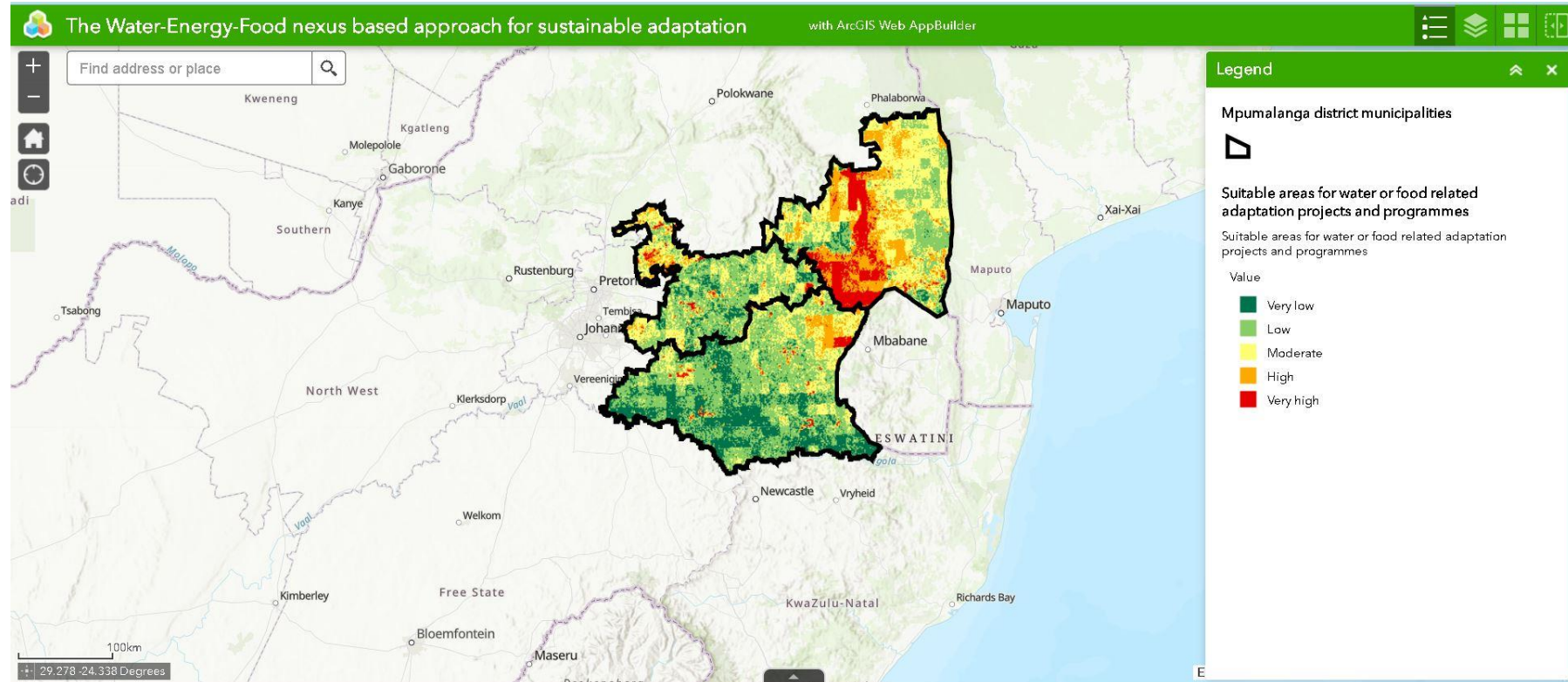
This is a web-based system used to visualize the spatial datasets used and derived in this study. It is developed using ArcGIS Pro, and ArcGIS online capability. The variables names as appeared in the web visualisation are listed and described in A.3.1.

Variables	Resolution/scale	Geospatial Web-Viewer (Names)	References
Climate change adaptation projects and programmes	-	Spatial Distribution of Adaptation Projects	<a href="https://nccrd.environment.gov.za/submissions/new/CA35433E-F36B-1410-8684-00528B626FB9">https://nccrd.environment.gov.za/submissions/new/CA35433E-F36B-1410-8684-00528B626FB9</a>
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( $\text{cm}^3/\text{dm}^3$ ), Silt (g/kg), Sand(g/kg), Bulk Density( $\text{cg}/\text{m}^3$ ), Clay Content(g/kg), Cation Exchange at pH7 (mmol(c)/kg, Nitrogen (cg/kg), Soil Organic Matter(dg/kg), pH (ph*10)	<a href="https://soilgrids.org/">https://soilgrids.org/</a>
Topographic information (derived from the DEM)	30 m	Elevation, Slope (%) and Aspect( $^{\circ}$ )	<a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a>
Land Use and Land cover dataset	Sentinel-2- 20 m Landsat- 30 m	Mpumalanga 1990, 2014, 2018	<a href="https://egis.environment.gov.za/data_egis/data_download/current">https://egis.environment.gov.za/data_egis/data_download/current</a>

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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	<a href="http://www.sasdi.net/metaview.aspx?uuid=a227be54418cf2cf678bc933accff10e">http://www.sasdi.net/metaview.aspx?uuid=a227be54418cf2cf678bc933accff10e,</a>
Climate indicators	8 km	See variables starting with 1p5 projections....	<a href="https://greenbook.co.za">https://greenbook.co.za</a>



<https://uparcgis.maps.arcgis.com/apps/webappviewer/index.html?id=72b00f23efaf41e490978fc5e3b492a4>

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

