WATER-ENERGY-FOOD (WEF) NEXUS FOR THE CROCODILE RIVER CATCHMENT

Report to the
Water Research Commission

by

S Walker[1], I Jacobs-Mata[2], BD Fakudze[2], M van der Laan[1], SN Masekwana[1], T Sawunyama[3] and S Machimana[3]
[1]Agricultural Research Council
[2]International Water Management Institute
[3]Inkomati-Usuthu Catchment Management Agency

WRC Report No. 3113/1/23
ISBN 978-0-6392-0576-2

January 2024

Obtainable from

Water Research Commission
Bloukrans Building, Lynnwood Bridge Office Park
4 Daventry Street
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

This is the final report of WRC project no. C2019/2020-00326.

EXECUTIVE SUMMARY

BACKGROUND

The Water-Energy-Food (WEF) nexus is a particular approach to address the linkages and dependencies between the three sectors. Much of the previous work has been at a national and regional scale, as the parameters are more easily available for whole countries or regions from various reporting mechanisms. This project provided a new approach by integrating Participatory Scenario Development and application of WEF tools at the Crocodile River Catchment level in Mpumalanga Province, South Africa.

AIMS

1. Review and compare currently available WEF analytical tools to identify a suitable WEF nexus analytical framework/tool; and establish and implement a stakeholder engagement plan in the Crocodile River Catchment.
2. Collect, document and visualise necessary catchment-specific data and information to analyse WEF components using the selected analytical framework/tool.
3. Co-develop a facilitative methodology for optimising WEF management decisions with decision-makers and document the process.
4. Develop scenarios (both consultative and technical) as a guideline for appropriate WEF policy recommendations at catchment level.
5. Provide an evidence-based guideline for policy recommendations from the WEF nexus analysis towards a resilient community.

METHODOLOGY

The project used mixed methods, both qualitative and quantitative approaches to address the objectives for the Crocodile River Catchment in Mpumalanga Province. The relevant literature was reviewed to establish the current state of research on the WEF tools and frameworks as well as the participatory type of engagements with stakeholders.

The pertinent WEF indicators were identified from the Analytical Livelihoods Framework (ALF) and Sustainability Performance Indicators (SPIs) together with the Water Footprint and Life Cycle Assessment (LCA) approaches. Indicators were calculated for the Mpumalanga Province across the Crocodile River Catchment and the City of Mbombela Local Municipality.

Stakeholder engagements included focus group discussions (FGDs), questionnaire surveys and workshops to both collect information as well as provide awareness about the WEF nexus concepts and approaches. Participatory Scenario Development (PSD) was used during a stakeholder workshop to facilitate the development of future scenarios for the catchment. Project team members made presentations at several catchment management fora meetings during the duration of the project to promote involvement and awareness of WEF amongst stakeholders.

Several team members registered as part-time postgraduate students during the project – namely two PhD students and two Masters level students.

RESULTS AND DISCUSSION

The review of current literature showed that there has been a wide range of published models, tools and frameworks that describe the interlinkages and dependencies of both the energy and agricultural sectors on water. From the shortlist of frameworks a few were selected to work with for the Crocodile River Catchment according to the applicability of the indicators and the availability of the relevant data. Some of the aspects that needed attention were that of scale – both spatial and temporal. As the catchment stretches across various district municipalities, it is not straightforward to integrate the information available from those political divisions with those of the geographical catchment boundaries. Some assumptions were made before calculating the indicators. The time scale was another

challenging aspect to deal with as many of the data were reported on different dates and for different time intervals, so again some assumptions were made and the best possible data were combined.

The Network of Adjacent Action Situations (NAAS)-approach was used to identify and analyse to observe the connections between key WEF-based decisions whether related to technical or institutional matters and leading to certain policy implementation scenarios. As the project stretches across three sectors (water, energy and food/agriculture), a transdisciplinary approach was used to highlight the need for consultation and effective communication across disciplines.

The context of the Crocodile River Catchment was described from a geographical and economic perspective. The Crocodile River itself rises near Dullstroom and flows eastwards towards the Mozambique border at Komatipoort. The main tributaries are the Elands- and Kaap Rivers with dams including the Kwena, Ngodwana and Witklip dams. Mbombela is the capital city of the Mpumalanga Province and the administrative and business centre of the Lowveld. Along the Crocodile River there are industrial areas around Mbombela, a paper mill at Ngodwana and sugar mills at Malalane and Komati.

About 40% of the land in Mpumalanga is arable and 31% of agricultural income is from field crops (mainly maize, soybeans and potatoes) while 15% is generated from horticultural crops (citrus, bananas, avocados) grown in the Lowveld region of Ehlanzeni District Municipality (DM). Macadamia nuts production increased by 240% in the 10 years since 2007 and is predicted to continue to expand. About 52% of agricultural income is from livestock production, although due to disease, little activity is in the Lowveld region. When considering the whole of the Mpumalanga Province, 55% of the water is used by agriculture and 26% for power generation; however, for Ehlanzeni DM the water used by the agricultural sector is 76%, with 11% for household use and only 10% for power generation, mining and manufacturing combined. The unemployment rate is high at 35% and is expected to increase in the future with a poverty rate of about 65% of the population in Ehlanzeni DM. Therefore, it is easy to see where the water stress originates from as the demand exceeds the available water supply.

WEF nexus indicators for the Crocodile River Catchment were calculated using provincial level information and expert local knowledge to achieve the best results. For water, the proportion of available fresh water per capita was 198 m^3/capita; economic value of water was ZAR23.86 per m^3; with a water demand of almost 1 Mm^3 pa and 91% of households with access to water. For energy, 90% of the population has access to electricity; the annual consumption in 2016 was 3200 kWh/capita; while greenhouse gas (GHG) emissions from energy generation were 900 g CO_2 per kWh and residential energy use per year was 12530 GWh. The agricultural and food indices used include 72.6% food security and 19.3% of the land being cultivated. As sugarcane is the dominant crop in the Lowveld along the Crocodile River, the following values were calculated: sugarcane water footprint 800 m^3t^{-1}; sugarcane water use efficiency 13.09 kg m^{-3} and average yield 90 t ha^{-1}. To have a balance between the three sectors, we used only three indicators per sector. The Sustainability Performance Indicators (SPIs) for Mpumalanga (2014-19) gave water stress at 0.87; households with access to water 0.91 and a water efficacy index of 0.83. For energy we used population with access to energy at 0.90; GHG emissions 0.55 and 0.38 for fraction of energy used in sugarcane production. For the food SPIs we used food insecurity index of 0.27; cultivated land at 0.19 and consumer price index of 0.18. These values were then plotted on a spider diagram to allow for easy comparison.

The Participatory Scenario Development (PSD) was conducted during a workshop with stakeholders from diverse backgrounds across all three sectors drawn from both the public and private sectors at national, provincial and local municipal levels in November 2020. The steps started with a review of the current situation and discussion groups considering the major drivers of development. Then sector-based groups developed a vision for the future for their sector based on local expert knowledge. Following this the scenarios were discussed and consensus achieved, before reviewing and evaluating the impacts and possible adaptation options for each sector. The scenarios chosen were business as usual (BAU) or “The Stagnant Nexus of 2050”, political/policy change, climate change and socio-economic change with the following details. For political/policy change, called “The Governance Imbalance of 2050”, one experiences the lack of commitment from government and changes in political power so that their political instability overshadows water and food security rights. For socio-economic change, called “The Global Market Frontier of 2050”, one could expect increased global competition (particularly for agricultural commodities), inequality to deepen, less industry support and sustainable access. For climate change in Mpumalanga, a hotter and drier climate is expected in future, although there can be more flooding due to extreme rainfall events, thus “Adapt and Thrive – Agriculture in the Climate Crisis of 2035”. Sector-specific visions were developed for urban or municipal areas, for industry, for agriculture, for water and for environment sectors. The specifics for each scenario were then expanded and combined to give a vision of the future. Under the socio-economic scenario, the need for compliance to international environmental and industrial standards was highlighted as a growing challenge. In the political/policy scenario one imagines self-interested politicians exerting influence over the administrative sphere and with less transparency. Under the climate change scenario there will be greater risk of both disease outbreaks and damage to infrastructure. For the BAU scenario there is a bleak future with continued declining trends of food security, service delivery and conflict resulting from further environmental degradation and water stress situations.

Focus group discussions and other surveys conducted by questionnaire confirmed and added detail to these future scenarios. At the municipal level, participants confirmed the continued degradation of the local environment and lack of concern for the effects of climate change. At the water management fora level, it was apparent that participants did not really have a good grasp of the interlinkages between water, agriculture and energy. However, they began to understand when it was presented as a 10 litre bucket of water (i.e. a limited supply) to be divided between the demands from communities for domestic household water, for irrigation and for energy generation that would benefit both the other sectors.

Recommendations for catchment level development decisions were developed by calculating the WEF indicators for three different scenarios that had been presented in the IUCMA strategic plan – namely changing to a more efficient irrigation method, changing to more water efficient and productive crops, and/or building a new dam. The three specific examples considered were: (1) to change from using centre pivot irrigation systems to using drip irrigation systems that are more efficient at delivering water to the root zone of the crops; (2) to replace some of the sugarcane plantings with macadamia orchards, as they use less water and produce a higher export value; and (3) the effect of providing additional water storage capacity and hence reliable water supply by the construction of Mountain View Dam on the Kaap River, a tributary to the Crocodile River.

A series of WEF nexus indicators were calculated for each of these scenarios to illustrate how the WEF approach can be used to inform such decisions. The WEF indicators used for these comparisons were water available for domestic consumption and for irrigation; for food and nutrients produced; amount of electricity available and the cost of infrastructure. In addition, environmental factors were added, namely the effect on biodiversity and the high and low water flows in the river. These indicators for the three interventions were then compared using a spider diagram. The development of the Mountain View Dam results in the highest values for water available for both domestic and irrigation purposes, as expected. However, it has detrimental effects on the biodiversity and the flow regime of the river. Comparing the production of sugarcane under pivot versus under drip irrigation and macadamia under drip irrigation results in more water available for both domestic and irrigation use due to lower water requirements per hectare. Macadamia scored highest values for food production and provision of good nutrient production although this may only be available to those employed in its production or to selected sections of the population. Macadamia also scored highest on maintaining river flow as it uses significantly less water per hectare. Therefore, the WEF indicators show that to allow the continued sugarcane production with valuable water in the Crocodile River is the least effective use of the available water and generates the lowest benefits for society and communities in the area. The production of macadamias, on the other hand, was shown to have the highest scores for five of the eight indicators. The building of the dam will give the highest scores for only two of the eight indicators. These results show how the WEF nexus analysis using a variety of indicators in such a situation can be used by catchment management authorities in their decision-making at a strategic and an operational level.

GENERAL

All the project aims have been achieved. The application of the WEF nexus indices was rather difficult due to the availability of data for the specific region of the Crocodile River Catchment which does not coincide with that of the district municipality boundaries. The WEF nexus indicators were calculated for Mpumalanga provincial level and for the City of Mbombela Local Municipality. WEF nexus indicators were calculated for the possible future scenarios as a guidance to decision-makers on how to proceed with development options. The guideline for facilitating PSD has been formulated showing specific steps to follow. The four principles must be kept in mind for development of WEF nexus applications – namely to make linkages and trade-offs between the three sectors more understandable; to ensure reliable, accurate and valid data; to use and adapt the WEF indices for many diverse situations and to be applicable across both temporal and spacial scales. These are considered vital to increasing the benefits and improving the application of the WEF nexus concepts to influence policy and resource planning processes across all scales of government.

CONCLUSIONS

This detailed WEF nexus analysis and participatory stakeholder development of future scenarios for the Crocodile River Catchment has illustrated how the WEF nexus indicators can be used by decision-makers. Through the stakeholder engagement at various levels from communities at grassroots through to municipal and provincial government officials, one was able to create awareness and build capacity around the understanding of the linkages and trade-offs needed when working with an inadequate supply of water. Despite the scarcity of detailed information at all required levels, one was able to evaluate the indicators using expert knowledge and by gleaning information from the literature and local informants. Therefore, this project has successfully shown the application of the Water-Energy-Food nexus concept at a catchment level to inform decision-makers and catchment management agencies.

RECOMMENDATIONS

It is recommended that these results be shared widely via a series of workshops with catchment management agencies and water managers. The WEF nexus indices should be used to develop a WEF nexus framework. It will also be worthwhile to engage with the agricultural and water sectors from grassroots level up to municipal and provincial government officials to apply WEF nexus indicators to other scenarios and decision points. This could assist in developing trade-offs and select options for ongoing productive use of the limited water resources. The “Facilitative Guideline for Policy-makers” should be widely distributed to be used by water management and catchment agencies. The methodology of applying WEF nexus indices to specific scenarios can help decision-makers in other catchments as well as local and district municipality level by engaging with experts.

ACKNOWLEDGEMENTS

The project team wishes to thank the following people for their contributions to this project.

Reference Group	
Prof. NS Mpandeli	Water Research Commission
Dr SN Hlophe-Ginindza	Water Research Commission
Dr L Nhamo	Water Research Commission
Dr C Nhemachena	Alliance for a Green Revolution in Africa
Dr T Chibarabada	Tongaat-Hulett Company
Dr D Tinarwo	UniVen
Dr M Jacobson	Penn State University, USA
Mr G Simpson	Jones & Wagner
Dr S Mathetsa	Eskom
Others	
Prof. Tafadzwanashe Mabhaudhi	UKZN & IWMI
Mr Obed Phahlane	Former ARC project team member
Dr Caroline Fadeke Ajilogba	Former ARC post-doctoral fellow
Mr Senzo Lukhele	IUCMA
Prof. John Ndiritu	Wits University supervisor (S Lukhele)
Dr Thokozani Kanyerere	University of Western Cape supervisor (S Machimana)
Prof. Charles Machethe	University of Pretoria supervisor (B Fakudze)
Dr Gugulethu Zuma-Netshiukhwi	ARC-NRE (Glen campus)
Ms Diana Mngomezulu	ARC-NRE (Glen campus)
Ms Masesabona Mathye	ARC-NRE (Glen campus)
Mr Sello Fusi	ARC-NRE (Glen campus)
Mr Harold Weepener	ARC-NRE (Arcadia campus)
Dr Thomas Fyfield	ARC-NRE (Arcadia campus)

This page was intentionally left blank

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

ACFS	The African Centre for Food Security
AGRA	Alliance for a Green Revolution in Africa
Agri	Agriculture
ALF	Analytical Livelihoods Framework
ARC-NRE	Agricultural Research Council – Natural Resources and Engineering
ARC-SCW	Agricultural Research Council – Soil, Climate and Water
BAU	Business as usual
BFAP	Bureau for Food and Agricultural Policy
CENSARDE	Centre for Sustainable Agriculture, Rural Development and Extension
CLEW	Climate, Land, Energy and Water
CSIR	Council for Scientific and Industrial Research
CTAFS	Centre for Transformative Agricultural and Food Systems
DALRRD	Department of Agriculture, Land Reform and Rural Development
DARDLEA	Department of Agriculture, Rural Development, Land and Environmental Affairs
DCDT	Department of Communications and Digital Technologies
DCG	Department of Cooperative Governance
DFFE	Department of Forestry, Fisheries and the Environment
DH	Department of Health
DHS	Department of Human Settlements
DiMTEC	Disaster Management Training and Education Centre for Africa
DM	District Municipality
DMRE	Department of Mineral Resources and Energy
DPME	Department of Planning, Monitoring and Evaluation
DPWI	Department of Public Works and Infrastructure
DSI	Department of Science and Innovation
DSD	Department of Social Development
DT	Department of Tourism
DTr	Department of Transport
DWS	Department of Water and Sanitation
ETC	Emergent Thematic Coding
FGD	Focus Group Discussion
GCIS	Government Communication and Information System
GHG	Greenhouse gas
gWh	Gigawatts per hour
IDP	Integrated Development Plan
IUCMA	Inkomati-Usuthu Catchment Management Area
IUWMA	Inkomati-Usuthu Water Management Area

IWMI	International Water Management Institute
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LM	Local Municipality
MAC	Message authentication code
MCR	Main control room
ML	Megalitre
MP	Mpumalanga Province
MuSSA	Municipal Strategic Self-Assessment
MW	Megawatt
NAAS	Network of Adjacent Action Situations
NAFU	National African Farmers' Union
NDMC	National Disaster Management Centre
NRF	National Research Foundation
NWA	National Water Act (Act 36 of 1998)
OTP	One-time password
PSD	Participatory Scenario Development
REDZ	Renewable Energy Development Zone
SALGA	South African Local Government Association
SAMAC	South African Macadamia Association
SANBI	South African National Biodiversity Institute
SANParks	South African National Parks
SASOL	South African (Steenkool) Coal, Oil and Gas Company
SAWS	South African Weather Service
SPI	Sustainability Performance Indicator
StatsSA	Statistics South Africa
TPTC	Inkomati Tripartite Permanent Technical Committee
TRAC	Trans African Concessions
UFS	University of the Free State
UKZN	University of KwaZulu-Natal
UKZN-CWRR	University of KwaZulu-Natal – Centre for Water Resources Research
Univen	University of Venda
UP	University of Pretoria
WEF	Water-Energy-Food
WF	Water footprint
WUA	Water User Association

This page was intentionally left blank

CHAPTER 1: INTRODUCTION

1.1 OVERVIEW AND BACKGROUND TO PROJECT

The Water-Energy-Food (WEF) nexus is a current research methodology used to address the integration of fields in sustainable development. Water resources in South Africa are a key factor that limits socio-economic development. Water resources and food are the basis for livelihoods and the development of a haven in arid and semi-arid regions, while energy is the lifeblood of economic development (Zhang et al., 2019a). The linkages across these sectors should be considered when planning interventions or development at various levels, namely community, catchment, provincial and national. Mpandeli et al. (2015) recommended using the WEF nexus approach to alleviate poverty, improve livelihoods and increase economic development at the country level.

The livelihoods of all South Africans are dependent on water resource use not only for domestic purposes, agriculture and/or industry but also to provide salient services such as ecosystem services (Conway et al., 2015). Livelihood is the ability to access the basic needs in life, which include food, water, energy and clothing (Krantz, 2001). The sustainable rural livelihoods framework approach is widely used in livelihood studies (Carney, 2003) as it emphasizes how people use their assets (natural, physical, social, human, financial) to maintain a viable livelihood with positive outcomes. In a livelihood approach, a detailed analysis of the factors that shape water, energy and food security is conducted at local or community levels. Since livelihood approaches capture the processes and contextual factors that shape adaptive capacity, the WEF nexus Analytical Livelihoods Framework (ALF) can be integrated into livelihood analysis (Mabhaudhi et al., 2019b). Some of these include the removal and purification of wastes, the commercial and subsistence supply of food, retention and storage of water, and transport of floodwaters. Other water services include those providing infrastructure for recreation and ecotourism as well as conservation of biodiversity through the maintenance of a variety of natural habitats. Reliance on rainfed agriculture, coupled with a poor resource base, exposes rural populations to the effects of climate variability and change, leaving them vulnerable to health hazards (Nhamo et al., 2019a). Reliance on such climate-sensitive sectors for livelihoods exposes rural populations to the impulses of extreme weather events and diseases (Mpandeli et al., 2018).

A Life Cycle Assessment (LCA) framework approach also complements the livelihoods approach as it is used to determine areas or activities of impact while comparing strategies for a production system. The LCA methodology has been expanded to a wider range of fields, including agriculture. The LCA provides a holistic methodology to investigate environmental impacts including improving system efficiencies that can decrease environmental burdens (Pryor et al., 2017). However, limited applications of LCA have been done in the South African agricultural sector, so this approach will be used to compare the agricultural systems in the lower Crocodile River Catchment, Mpumalanga Province.

South Africa's National Development Plan (NDP) intends to increase agricultural land by extending the area under sustainable land management and reliable water control systems. This includes improving rural infrastructure and trade-related capacities for improved market access to increase food supply and reduce hunger. Therefore, the WEF nexus can be an important decision support tool to achieve these NDP targets. A WEF decision support tool can assist in assessing the optimal combination or balance of resource allocation to reach these goals. Such an approach can protect vulnerable communities, landscapes and biodiversity from degradation as the WEF nexus provides tools to analyse complex interrelated resource systems as well as to manage resources in a cohesive manner (Nhamo et al., 2019b). Such analysis will provide recommendations for innovative policies concerning the water, food and energy sectors, ensuring improvements in livelihoods and sustainability of resources for human wellbeing. Consequently, well-outlined evidence-based policies can have a high potential to improve the country's resilience to natural disasters and extreme events. At present, South African water utilization and conservation policies focus on individual sectors, namely agriculture, domestic and municipal uses, industry, recreational and ecotourism. However, there are many conflicting demands for limited water resources. Therefore, there needs to be a negotiated balance between the demands and benefits expected from each sector. This type of WEF nexus methodology allows for comparative studies of quantitative relationships across sectors in resource management, enabling one to account for cross-sectoral synergies and trade-offs using specially developed tools and indices (Nhamo et al., 2019b). A variety of WEF nexus tools have been developed for a range of users, at different levels and for different purposes. However, one of the main stumbling blocks is the incompatibility, inaccessibility and unavailability of data (McCarl et al., 2017b), together with limitations to data sharing and the costs thereof, with the inconsistency of time and spatial scales across the nexus (Cash et al., 2006; Bhaduri et al., 2015). An important consideration worth noting is that the rationalist scientific endeavour assumes that these models speak an objective truth to power. But the politicisation of scientific evidence shows that the use of science can be political and is not necessarily objective, that power is an important influence in determining which knowledge will be considered legitimate and which not, and that data is never neutral. We, therefore, must acknowledge the imperfect/non-linear process of communication and translation that WEF nexus models and tools will follow in communicating their nexus scenarios to intended and unintended audiences.

Another consideration to note is that the vast majority of WEF nexus models and tools are technical in nature, and few are in a format that is easily understood by those for whom they were made. How then do we translate this technical language into a process that is easily understandable? We believe that the answers are found in the development of facilitative processes that accompany the communication and translation of specific WEF nexus tools to different decision-makers. As Daher et al. (2017) note, decision-makers differ in scope and capacity, having to make decisions at small association, local, regional, national or international levels. As such, their interests and the complexity of their critical questions will differ. The challenge of modelling the WEF nexus is to provide a clear, simple, yet comprehensive way of unpacking nexus inter-dependencies and trade-offs. An accompanying facilitative process supports the decision-making process without taking away the decision-maker's autonomy to make decisions. Rather, it enables the decision-maker to ask different questions, consider the non-linear trajectory that evidence takes in informing policy, and grapple with power asymmetries and other socio-political dynamics that are not able to be modelled. In essence, while WEF nexus models allow trade-offs to be presented to the decision-maker who would prioritize them and make choices based on simplified results (Daher et al., 2017), an accompanying facilitative process allows the decision-maker to grapple with social complexities that are not easily simplified.

Therefore, a need exists for the development of stakeholder-centric WEF analytical tools for a particular audience with unique needs. This must be accompanied by the development of appropriate facilitative processes that allow for communication, knowledge transfer, and uptake of such tools and approaches by users. This will enable them to achieve the intended purpose of advancing our understanding, informing planning processes, informing policy development, and/or helping to facilitate decision-making at an operational level.

In this study, we document the components of a WEF nexus for the Crocodile River Catchment by identifying the causes of water stress for sectors in the catchment. A participatory approach will be used to develop scenarios, including feasible infrastructure and alternative cropping system interventions, from which to draw sustainable recommendations that include nexus interlinkages between the WEF parameters across all the sectors.

1.2 PROJECT OBJECTIVES

Overall objective:

To apply Water-Energy-Food (WEF) nexus models and/or a framework at a catchment level for the Crocodile River Catchment in Mpumalanga Province, including the co-development of facilitative decision-making methods.

Aims:

1. Review and compare currently available WEF analytical tools to identify a suitable WEF nexus analytical framework/tool; and establish and implement a stakeholder engagement plan in the Crocodile River Catchment.
2. Collect, document and visualize necessary catchment-specific data and information to analyse WEF components using the selected analytical framework/tool.

3. Co-develop a facilitative methodology for optimizing WEF management decisions with decision-makers and document the process.
4. Develop scenarios (both consultative and technical) as a guideline for appropriate WEF policy recommendations at catchment level.
5. Provide an evidence-based guideline for policy recommendations from the WEF nexus analysis towards a resilient community.

1.3 SCOPE AND LIMITATIONS OF THE STUDY

The WEF nexus as a framework is used to address the integration of resources for sustainable development. Whereas most nexus models are technical and do not include and integrate other tools such as interaction with stakeholders via a facilitative process, WEF nexus tools have been developed according to the users, decision-makers and stakeholders. The WEF nexus approach has been applied at national and regional levels across southern Africa (Nhamo et al., 2019a&b). However, some indicators cannot be used at a catchment level, as individual catchment data is too limiting to be representative of, for example, self-sufficiency in water, energy or food, but have inter-catchment transfers for each of these commodities. This usually means that the scope needs to be widened. Although water resources in South Africa are key to livelihoods and development, water scarcity limits socio-economic development in semi-arid regions, while another factor – energy – is vital for economic development (Zhang et.al., 2019b). Linkages across the three sectors (water, energy, agri-food) should be considered when planning interventions or development at various levels, namely regional, national, provincial, catchment and community levels. Although the WEF nexus has been documented at a larger scale, there are few studies at the catchment or community level in southern Africa (Mabhaudhi et al., 2016). The WEF nexus offers significant opportunities for coordinated approaches to increase resilience in the future, as Mpandeli et al. (2015) recommended using the WEF nexus approach to alleviate poverty, improve livelihoods, and increase economic development together with job creation at a country level.

CHAPTER 2: LITERATURE REVIEW

2.1 WATER-ENERGY-FOOD (WEF) NEXUS BACKGROUND

Water, energy and food are essential resources that sustain life and livelihoods (Nhamo et al., 2020a). The three resources are interlinked and interdependent in such a way that any disturbances in one influence the others. Simpson and Berchner (2017) state that water, energy and food are three key pillars for human livelihoods to develop and thrive. Food production and food security are major aspects of agriculture. However, increasing pressure exerted on the industry by climate change, land degradation, population growth and demands, as well as urbanization of communities, has led to the need to sustainably manage resources such as water, food and energy (Nhamo et al., 2020a). These factors increase the competition for natural resources by increasing pressure on agricultural production of food, fibre, energy and other high-value by-products. This also causes elevated concerns related to environmental impacts associated with the needs of a growing population in a country where limited rainfall, droughts and food shortages are a big concern. The challenges of managing water, energy and food resources simultaneously need to be resolved urgently without compromising natural resources, by addressing the multiple and sometimes conflicting objectives of the various sectors and stakeholders (Purwanto et al., 2021).

The relationship between these resources is known as the water-energy-food (WEF) nexus (Nhamo et al., 2020a). WEF sectors are interlinked and so are the challenges, so much so that focusing on one sector can potentially aggravate and/or transfer stresses to other sectors. Simpson and Berchner (2017) state that the pillars are not independent but have a multitude of interconnections and trade-offs existing between them. The WEF nexus is a transformative approach that aims to increase natural resource use efficiencies and informs coherent strategies for sustainable natural resources management (Nhamo et al., 2020b). When the WEF nexus is applied as a conceptual tool, it provides a framework for understanding the complex interrelations, synergies and trade-offs between water, energy and food (Lawford, 2019; Nhamo et al., 2020b). Simpson and Berchner (2017) state that water is utilized in agricultural production for irrigation as well as processing of the products. Water is essential for energy generation and the same energy is used for pumping water and mechanization of agricultural activities. A lack of sustainable resource management like water will lead to adverse threats to food security locally and worldwide (Le Roux et al., 2018). Fernández-Ríos et al. (2021) used the WEF nexus approach to profile food security using WEF nexus indicators and the Sustainable Development Goals (SDGs) as tools. When considering the SDGs, Mabhaudhi et al. (2021) states that the Analytical Livelihoods Framework (ALF) is one of the tools that has been used for WEF nexus analyses by assessing measurable indicators. WEF nexus models and decision-support tools have been developed at a particular temporal and spatial scale, thus including both time and area/location. WEF nexus data systems need to reflect the site specificity of the study region and incorporate the key activities taking place to describe the unique challenges being faced between different areas (Jacobs-Mata et al., 2021). In several WEF nexus studies, focus has been placed on the regional or national levels, however, there are few studies at the catchment or community level in southern Africa (Mabhaudhi et al., 2016). Following a review of the available WEF nexus tools and the data requirements, the outputs provided will be assessed in relation to the aim of using the WEF framework to address water resource allocation in a heterogeneous catchment case study. The selected framework needs to use data from various sources to provide indicators that stakeholders can use in decision-making and policy formulation. The descriptive parameters for each segment of availability and accessibility of water, energy and food will be developed according to the specific activities within a specific catchment.

2.2 WEF NEXUS FRAMEWORK AND TOOLS

2.2.1 Introduction

Different potential users of WEF nexus tools have different specific questions that need answers. Those users may come from government, business or civil society agencies, and be interested in different levels of detail and information regarding their resource allocation questions. Also, these different users may operate within different constraints of time, finances and human resources. In such cases, simplified or 'rapid nexus assessment' tools tend to be more suitable and provide valuable initial assessment, which can then bridge to the use of more advanced tools (Daher et al., 2017).

Thus, the purpose of this literature review is firstly to review methods for comparing widely applied nexus tools identified by international organizations (UNDG, 2016; IRENA, 2015; FAO, 2014), South African institutions (Nhamo et al., 2020b; Mpandeli et al., 2018; Mabhaudhi et al., 2016) and in other primary literature sources (Kaddoura and El Khatib, 2017). The second component is to review constructed criteria motivated by systems engineering and user-experience (UX) concepts to measure the respective 'simplicity' or 'complexity' of the tools.

The WEF nexus framework tools identify different water sources, needs, consumption and withdrawal requirements from those sources. In terms of food they consider local food production levels (sugarcane) versus imported food and other agricultural crop production. For energy, the tools will identify sources of energy for water, agricultural production, and for other sectors such as electricity. The applicable data selection can be daily, monthly or annual. The tools can be used to interpret data and create different scenarios with varying water-energy-food self-sufficiencies. This assists in decisions about land requirements (ha), selected crop yield (ton), energy requirements (kJ), energy consumption through import (kJ), type of energy to suit selected scenarios, import and export management by government officials, and other decision-making stakeholders such as the municipalities. The results can be related to policy and regulation of export and import of agricultural products and energy regulators.

Various WEF nexus framework tools have been developed at different levels, internationally and nationally. Framework tools will be applied, compared and tested for relevance to decision-making, and these include the use of Sustainability Performance Indicators (SPIs) by Zarei et al. (2021). The procedures used will include a quantitative process to calculate a range of indices for each of the component sectors that can be used to assess WEF nexus trade-offs. The integration of the various tools may lead to the development of an applicable WEF nexus framework specifically for use at provincial, municipal and catchment levels. The applicable indicators linked to the most favourable WEF securities are SDG 2, 6 and 7. When considering the SDGs and links to WEF, Mabhaudhi et al. (2021) used the ALF as one of the tools in WEF nexus analysis as it can be assessed through measurable indicators. Alternative approaches such as Life Cycle Assessment (LCA) will be used as calculation tools for some of the major crops grown in the catchment. The assessments will be done to compare sugarcane and macadamia orchards – the two important or base crops in the province – as they include biophysical indicators of crops such as water use efficiency and footprints.

2.2.2 WEF nexus index system based on different scales

The WEF nexus seeks to challenge boundaries and connect discourse between academics, experts and policy-makers, who possess different forms of technical knowledge and disciplinary perspectives. Cash et al. (2006) highlight the variation of scales across the nexus. While nexus thinking is driven by the quest to address global problems it is often local scales (e.g. household, regional and national) where nexus practice appears to be advantageous.

2.2.2.1 Urban WEF nexus versus other nexus scales

In the last decade, several approaches have dealt with the disarray and the abundance of tools. Ness et al. (2007) developed a framework to classify sustainability assessment tools based on their approaches and focus areas. At the local level, definitions mainly focus on the WEF system itself, ignoring the nature-human interaction underpinning the nexus except for the definition from a techno-ecological view by Martinez-Hernandez et al. (2017).

Based on the essential nature-human interaction, the local WEF nexus is defined here as a set of complex linkages across the natural and human systems, including resource interdependence at a larger scale and governance at the local scale. This set of linkages consists of three sub-nexuses, namely the core, peripheral and interactive nexuses (Fig. 2.1).

Firstly, the core nexus represents the interactions between water, energy and food, including processes such as production, processing, storage, pumping, distribution, transportation, consumption and waste disposal at the city scale. Linkages within the core nexus can be characterized into a technical flow, physical flow and structural flow. Induced by technical feasibility and policy intervention, technical flow is similar to input-output flow, which is a hotspot in nexus research, addressing trade-offs and synergies among WEF interactions to improve efficiency.

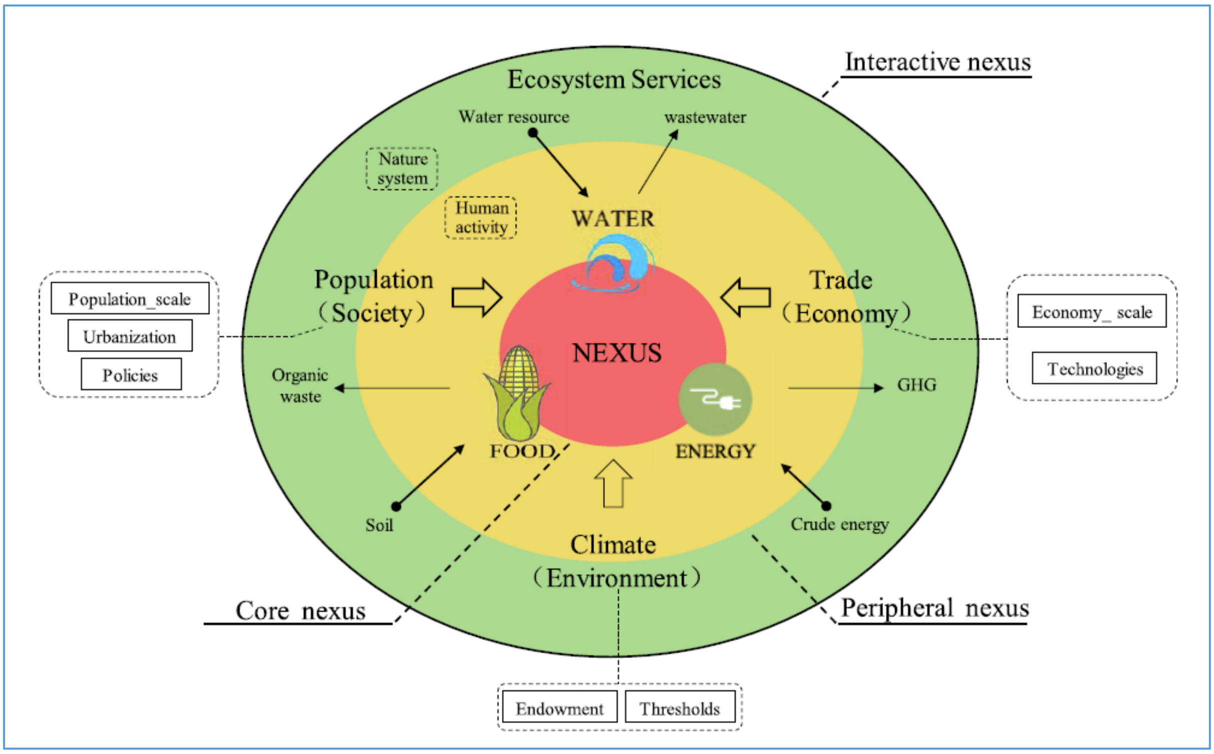


Figure 2.1 Conceptual framework of local WEF nexus from nature-human interaction view (Jiang, 2017).

Physical flow relates to WEF resources located in various city locations through land use change and infrastructure construction. Different scenarios are possible here, for example centralized and decentralized wastewater treatment plants. A common example in many countries is a dam construction which influences connections between urban water provision, hydropower and food production, with water connecting energy and food.

Secondly, the peripheral nexus gives expression to the interaction between WEF systems and the dynamic overall urban system (Fig. 2.1). Consisting of urban social, economic, ecological, technical and political components, factors such as population, trade and climate drive the variation of supply, demand, distribution and structure in WEF systems. For example, population growth will increase WEF demand, while urbanization changes the demand structure with the growth of the middle class. Climate change affects the natural system and human activity by altering ecological thresholds and WEF resource availability in the urban district, which could decrease the reliability of the current WEF infrastructure system.

Thirdly, the interactive nexus is the interaction between the natural environment system and human activity, demonstrating the supply limitation originating from the natural system and indicating that human activity should be performed within planetary boundary thresholds (De Grenade et al., 2016). The natural system provides water resources, soil and primary energy for the urban WEF provision, and effectively disposes of waste from human activity. In the human activity layer, the focus is on the balance between ecosystem demand and human activity demand in WEF resources.

2.2.2.2 WEF nexus interactions and interconnection

Cities are not only resource islands (Perrone et al., 2011) but are also concentrated centres of production, consumption and waste disposal (Grimm et al., 2008). The processes in each system include water, energy and food. Firstly, the water perspective is illustrated in Fig. 2.2. A description by Jiang (2017) of an urban interaction in the water system includes pumping, transportation, desalination/purification, reclamation, storage, distribution, production (agricultural, industrial), domestic and environmental use, wastewater recycling, wastewater treatment and sludge disposal (anaerobic digestion). The urban water system pumps groundwater (G-water) and surface water (S-water), and reclaims rainwater (R-water) from the natural system at lower economic cost than employing inter-basin water transfer and seawater desalination. The urban green area includes waterbody, grassland and forest attached to parks, production areas and institutions, and is an intersection area between nature and human activity. Water use in the urban green system could be defined as environmental use.

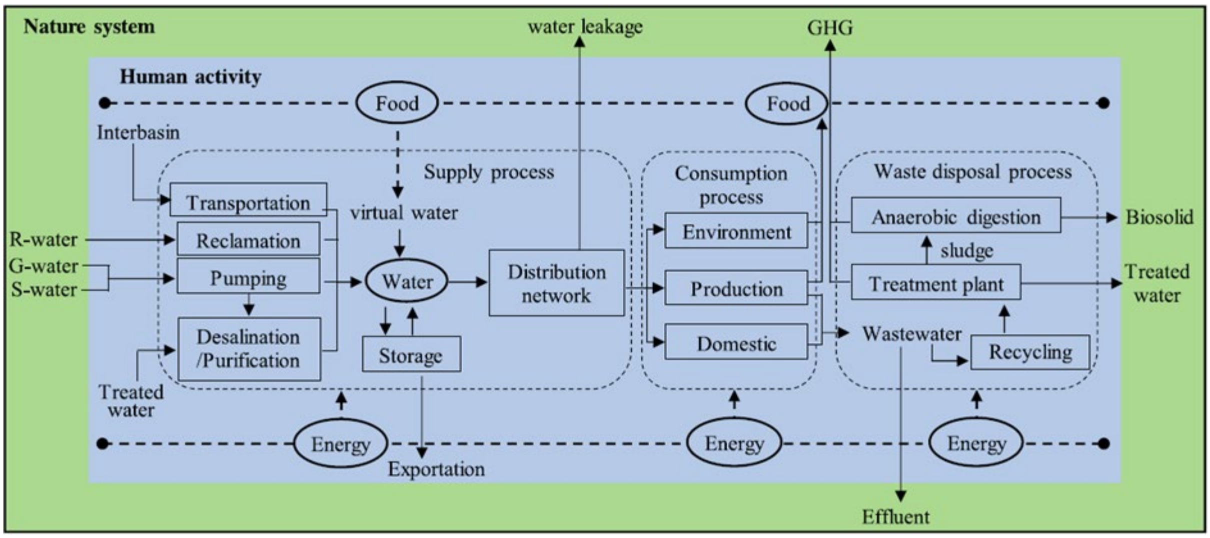


Figure 2.2 Water perspective on urban WEF nexus (Jiang, 2017).

Secondly, the energy perspective is illustrated in Fig. 2.3. Primary fuels and electricity are two critical aspects of energy both imported and generated in urban areas (Salmoral and Yan, 2018). Urban processes are extraction (mining) and processing (refining), generation, distribution, production, transportation, residential and commercial construction, and waste recycling, reuse, incineration and disposal through landfill. Extracting and refining fuel (coal, crude oil, natural gas) or transforming renewable energy sources (solar, hydropower, tidal energy, bio-crops) are often water-intensive processes.

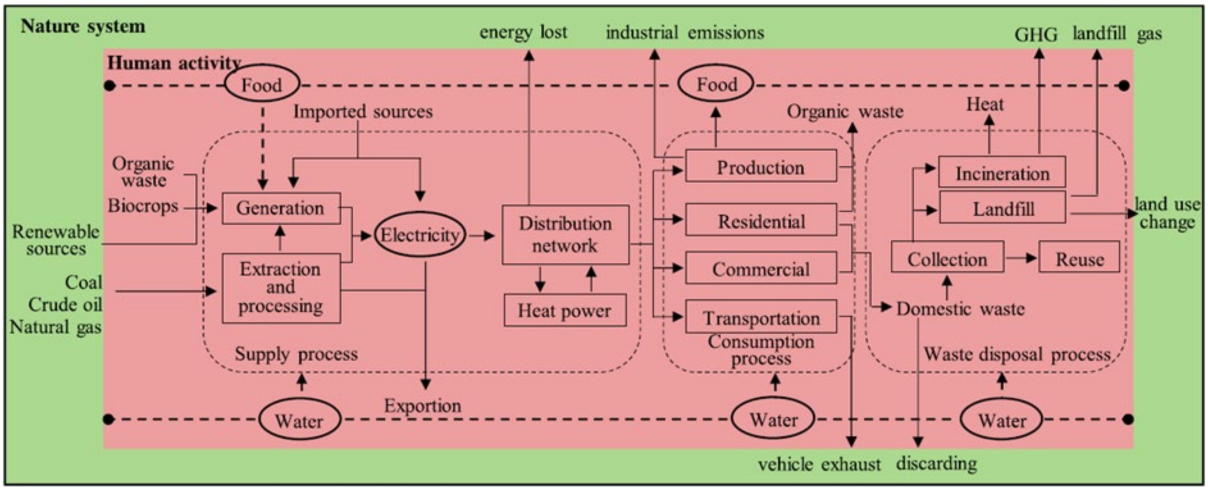


Figure 2.3 Energy perspective on urban WEF nexus (Jiang, 2017).

Energy production attracts a good deal of attention in current nexus research, especially water in coal and natural gas extraction (Water in the West, 2013), water as cooling liquid in thermal power generation (Chang et al., 2016), and water for biomass cultivation and processing (Hoff, 2011). But hot water consumption in residential buildings and water as an energy carrier have been largely ignored. The process of energy production from coal burning has impacts on regional air quality and does harm to human health (Ebenstein et al., 2017).

Thirdly, the food perspective is illustrated in Fig. 2.4. Urban food can be categorized into raw and processed products. Raw products are grain from crop farming, and meat, eggs and milk from livestock farming. Processed products are animal feed, bread and sugar which is refined or made from raw products. Urban activities here are farming, processing, transportation, storage, transformation, cooking, catering, feeding and food waste disposal.

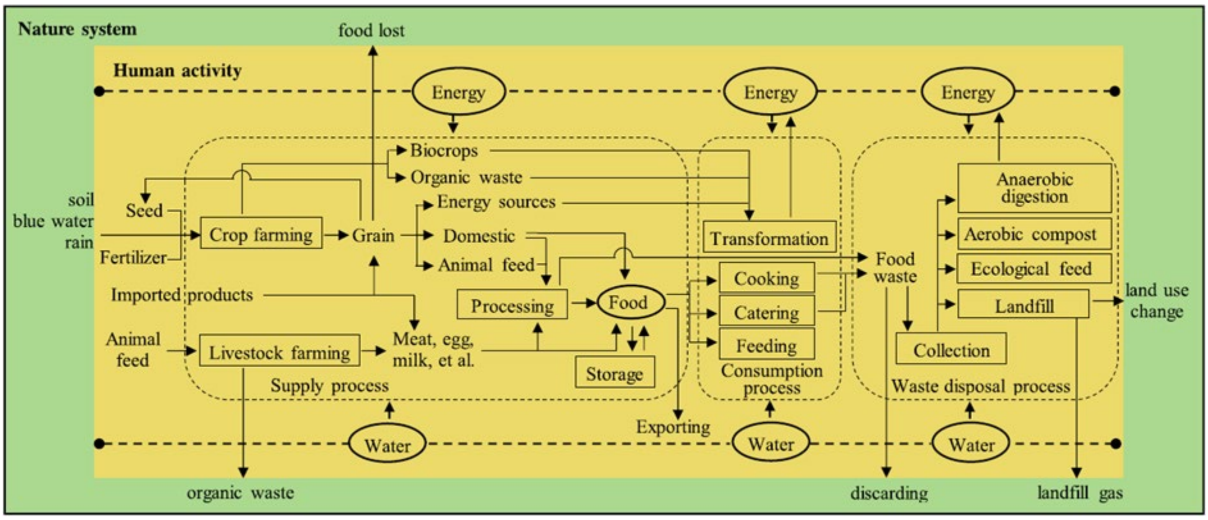


Figure 2.4 Food perspective on urban WEF nexus (Jiang, 2017).

Agriculture has a high water consumption, low energy intensity sector, consuming most farm energy on groundwater pumping and chemical fertilizer. Reducing water losses with pressurized pipes is an effective way to reduce water consumption in agriculture (Wakeel et al., 2016), but in practice a water efficient pressurized delivery system consumes a large amount of energy (Siddiqi and Fletcher, 2015), resulting in nexus point shift from groundwater pumping to water delivery. Agriculture pollutes the water system and causes an environmental change through the high use of fertilizers and pesticides, forming long-term, non-point source pollution in downstream environments both locally and nationally (Cai et al., 2018).

2.2.3 Driving forces in the WEF nexus systems

The various driving forces and interactions need to be considered across the three sectors. Firstly, in determining the water equations, the amount of water consumption at the catchment scale will be selected as the Y variable. The amount of water consumption (W_C) will represent the state of the catchment water systems including evaporation and other identified factors unique to the catchment. Studies from Wakeel et al. (2016) and Kroll et al. (2012) explain how drivers affecting (W_C) come not only from processes in WEF sub-systems such as water sources (surface water, groundwater or recycling water) affecting water consumption because of their various prices, but also from catchment water management behaviour and policies such as social and economic system and natural resource supply.

Secondly, in the energy equation, energy consumption (E_C) also works as another Y variable (urban or catchment use in the case of this study), because energy consumption is critical in promoting urban development and industrial production at the local scale. In this equation, drivers include water pumping and wastewater treatment and other identified users from the water sub-system and population from the society sub-system, as well as various others (Fig. 2.3).

Thirdly, in determining the food equation, food production (F_P) is the Y variable for food as an important output and major water consumer in the urban area. Food production is significantly affected by water, land, ecosystem and the urban economy, as well as fuel energy supplies.

To achieve the normality of the indicators deliberated in the previous paragraphs, a logarithmic form will be utilized for all variables. Based on the above three equation explanations, the vector Y could be defined as (W_C; E_C and F_P), while details of vector X (or indicators) from driving factors (Table 2.1) and methods (Fig. 2.2).

Table 2.1 Description of driving factors and indicators with their respective specifications and units (after Huang et al., 2020)

Vector Y	Driving Factors	Indicators	Specifications	Units
W_C, E_C	Food Process	Food Production (F_P)	Amount of grain produced on an arable land in a catchment	Tonnes
	Water process	Total water resources (TWR)	Amount of surface water and groundwater in a catchment	Cubic meter (m^3)
W_C, E_C, F_P	Water process	Total groundwater pumped (TGP)	Amount of groundwater pumped in a catchment area	m^3
W_C	Food process	Effective irrigated area (EIA)	Area of irrigated land where water demand is met in a normal year	Hectare
	Energy process	Thermoelectricity generation (TG)	The amount of electricity produced from thermal plants	Tonnes of coal equivalent
	Economy	Investment of water conservancy, environment & public facilities management (WEPI)	The amount WEPI in a catchment area / municipality or district	ZAR

Vector Y	Driving Factors	Indicators	Specifications	Units
	Environment	Catchment green land (UGL)	Total area occupied for green projects, including park green land	Hectare
	Society	Settlement population (SP)	Permanent resident population in urban area	Capita
	Environment	Waste gas emission (WGE)	Total waste gases (SO, CO, etc.) emitted in urban area	Tonnes
E_C	Society	Vehicle volume per 10 thousand capita (VV)	Amount of vehicles owned by 10 thousand capita	Per capita
	Society	Completed area of commercial building in previous year (CACB)	Total area of commercial building to be used in the estimated year	Hectare
	Economy	Secondary industry rate (SIR)	Percentage of output value of secondary industry in catchment GDP	Percentage
E_C, F_P	Environment	Wastewater treatment capacity (WWTC)	Maximum amount of wastewater treated per day	m^3
	Food process	Chemical fertilizer used per sown area unit (CFSA)	Amount of CFSA in urban area to indicate soil quality	Tonnes
	Economy	Investment of power, thermal, and water supply industry (PTWI)	Total amount of PTWI in catchment area	ZAR
F_P	Economy	Investment of agriculture, forestry, animal husbandry and fishing industry (AFAFI)	The total amount of AFAFI in catchment area	ZAR
	Water process	Water consumption (W_C)	Amount of water consumed in catchment area	m^3
	Environment	Damaged area (DA)	Area damaged by disaster in crop farming	Hectare
	Society	Gross domestic production per capita (AGDP)	Amount of GDP per capita in catchment area	ZAR
	Food process	Cropping area planted (CAP)	Area sown with crops in catchment area	Hectare

Table 2.2 Description of methods, geographic scale and model type as well as usefulness (after Huang et al., 2020)

Method	Geo-graphical scale	Model type	Software	Purpose	Application category
Methods covering the Water-Energy nexus					
EI – Energy Intensity	City level	Quantitative analysis model	No software	Quantify energy flows in urban water systems	Understanding
Linkage analysis	City level	Quantitative analysis model	No software	Explore the structure and interconnection of both water and energy resources in cities	Understanding
UWOT – Urban Water Optioneering Tool	City level	Quantitative analysis model	Online tool UWOT	Quantify energy use in urban water supply systems	Understanding
MRNN – Multi-Regional Nexus Network	City & regional level	Quantitative analysis model	No software	Explore interconnection of energy consumption & water use for urban agglomerations	Understanding

Method	Geo-graphical scale	Model type	Software	Purpose	Application category
System dynamic approach	Regional level	Integrated model	No software	Long-term regional water & energy resources management	Understanding
Jordan's framework	National level	Integrated model	No software	Link decision-making to higher use efficiencies of water & energy	Governing
SATIM-W (Thirsty Energy initiative of the World Bank & South African government)	Regional level	Integrated model		Developed by Energy Research Centre at University of Cape Town to link & model water-energy & the economy	Understanding
Methods covering the Water-Energy-Environment nexus					
Integrated Model to Assess the Global Environment – IMAGE	Global / regional level	Integrated model	No		Understanding
UWtoA – Urban Water to Air Model	City level	Quantitative analysis model	Pacific Institute; A spreadsheet model	Simulate energy use & air quality in urban water systems	Understanding
WESTWeb – Water-Energy Sustainability Tool Web	City level	Quantitative analysis model	University California, Berkeley; Online tool	Assess energy use & GHGs in water supply & utilization system	Understanding
GLEW – Great Lakes Energy Water model	Regional level	Simulation model	Studio Expert 2008	Impacts of electricity generation portfolios on water resources	Understanding
REWSS – Regional Energy & Water Supply Scenarios model	Regional level	Quantitative analysis model	Open source REWSS	Calculate the annual environmental impacts of supplying energy & water to a specified region	Understanding
Integrated CGE – Computable General Equilibrium	National level	Simulation model	No software	Forecast the impact of energy tax policy on energy & water use & demand	Governing
CMDP – Competitive Markov Decision Process model	National level	Simulation model	No software	Impacts of carbon taxes & water on electricity systems	Understanding
MA – Meta-system architecture model	National level	Quantitative analysis model	No software	Quantify material & energy flows in national electricity, water & wastewater systems	Understanding
SPATNEX-WE – SPAtial & Temporal NEXus-Water Energy	National level	Integrated model	No software	Track energy flows & water withdrawal & consumption throughout water & energy systems	Implementing
Modified AQAL All Quadrants All Levels	Regional & national level	Integrated model	No software	Explore the water & electricity linkages under climate changes, & assess policy implications	Implementing
Mixed-unit MRIO – Multi-Regional Input−Output analysis model	National & trans-boundary level	Quantitative analysis model	No software	Life cycle assessment of water use in energy production, & environmental impacts	Understanding

Method	Geo-graphical scale	Model type	Software	Purpose	Application category
TIAM-FR – TIMES Integrated Assessment Model	National & trans-boundary level	Integrated model	MINES Paris Tech Center of Applied Maths; No	Forecast water demands in energy optimization considering climate changes	Understanding
WCCEM – Water & Carbon Conscious Electricity Market	National or global level	Simulation model	No software	Assess water and carbon taxes impacts on national electricity generations, and to control water usage & GHGs	Understanding
RRP – integrated rainfall-runoff model & power system model	Multi-scales	Integrated model	No software	Impacts of water flow and temperature on power systems	Understanding
WATER – Water Analysis Tool for Energy Resources	Multi-scales	Quantitative analysis model	Argonne National Laboratory; Online tool	Assess water use and quality in fuels production	Understanding
WEAP-LEAP Water Evaluation & Planning system & Long Range Energy Alternatives Planning	Multi-scales	Integrated model	SEI; WEAP and LEAP software	Policy impacts on water and energy demands as well as GHGs	Governing
CSIR Green Book tool	National level	TBC	TBC	TBC	Implementing
CSIR Water multi-decision support tool	Catchment level	Simulation model	TBC	TBC	Understanding / implementing
Variable Resolution Earth System Model – VRESM	Regional level	Integrated model	TBC	Couples the atmosphere, oceans & land	Understanding / implementing
Methods covering the Water-Energy-Food nexus					
ZeroNet DSS – Decision Supporting System	Regional level	Integrated model	Several free software	Decision support in resource management in basin	Governing
Nexus Assessment 1.0 FAO	Regional & national level	Quantitative analysis model	Online rapid appraisal tool	Qualitative and quantitative assessment of Nexus	Governing
IAD-NAS – Institutional Analysis & Development Frameworks with value chain analysis	National level	Quantitative analysis model	No software	Impacts of institutions and policies on the sustainability of water, food and energy	Governing
WEF Nexus Tool 2.0	National level	Simulation model	Online tool	Quantitative assessment and forecast of WEFN	Governing
DEA – Data Envelopment Analysis	Multi-scales	Quantitative analysis model	No software	Evaluate regional input-output efficiency of resources holistically	Understanding
WEFO – Water, Energy & Food security nexus Optimization model	Multi-scales	Integrated model	WEFO tool	Quantitatively assess the interconnections and trade-offs among resource systems as well as environmental effects	Governing
Basic Linked System (BLS) model	Multi-scales	Integrated model		A world food system model developed by the International Institute for	Understanding

Method	Geo-graphical scale	Model type	Software	Purpose	Application category
				Applied Systems Analysis (IIASA).	
Urban agriculture (rain harvesting)	City Scale	Quantitative Analysis Model	No	Applies economic analyses and modelling	Knowledge Generation
WWEF Nexus Framework	National Scale	Quantitative Analysis Model	No	Define & quantify interconnectivity between Water-Energy-Food	Governance
Methods covering the Water-Energy-Food / Water-Energy-Land-Climate nexus					
Nexus Trade-off Assessment Tool – SWAN	Multi-scales	Integrated model	World Wind visualization technology	Agricultural water visualization platform, focusing on irrigation of sugarcane in eSwatini	Understanding
MSA Multi-sectoral Systems Analysis	City level	Quantitative analysis model	Matlab tool	Understand resource flows as well as human effects on the urban metabolism	Understanding
GCAM-USA – Global Change Assessment Model	Regional level	Integrated model	Open source tool	Long-term analysis of water withdrawal & demand in electricity sector of USA states	Governing
PRIMA – Platform for Regional Integrated Modelling and Analysis	Regional & national level	Integrated model	Velo	Simulate the interactions among climate, energy, water & land at the decision-relevant spatial scale	Implementing
MuSIASEM – Multi-Scale Integrated Assessment of Society & Ecosystem Metabolism	Regional & national level	Integrated model	FAO, free online tool	Assess metabolic pattern of energy, food & water related to socio-economic & ecological variables	Governing
Foreseer	National and trans-boundary	Integrated model	University of Cambridge Online tool	Map flows of water, energy, land use and GHGs	Understanding
Modified SWAT – Soil & Water Assessment Tool	Trans-boundary	Integrated model	Open source model	Water provisioning to each economic sector in transboundary context	Understanding
TRBNA – Transboundary River Basin Nexus Approach	Trans-boundary	Integrated model	UNECE, NS	Assess the WEFEN in transboundary river basins	Implementing
CLEWs – climate, land, energy & water	Multi-scale	Integrated model	Open source tool OseMOSYS	Assess climate impacts on resources and supply help in policies evaluation	Implementing
Water footprints – WEF nexus	Multi-scales	Footprint Method	No	Ecological footprint, diet/food, virtual water trade, & water governance	Governance
Biophysical & Economical Modelling of WEF Nexus Systems	Multi-scales	Uses indicators (physical & socio-economic)	No	Use crop &, economic models of land use, with water quality model	Knowledge Generation
Analytical Livelihoods Framework – ALF	Multi-scales	Integrated model	Under development	Trade-off analysis, integrated use	Knowledge Generation

2.2.4 WEF models and tools

A number of WEF models and tools and have been used and developed over the last several years. They have also been applied at a variety of scales, both temporal and spatial. These range from local urban scale to national, regional and continental spatial scales, and the time scale can be from daily through weekly and monthly to seasonal, annual and decadal. The inputs and outputs needed for such models and tools will depend on both scales of application. The use of the outputs from such models can be used for day-to-day management decisions by various role-players, for medium-term monthly planning activities or for tactical seasonal or strategic long-term planning for the catchment or country as a whole. Therefore, the selection of a WEF model or tool will depend upon the stakeholders' or clients' needs and requirements. Some of the most useful WEF models and tools have been investigated and will be described in the following sections with a summary of the various aspects for comparison in Table 2.3.

2.2.4.1 Water, Energy and Food Nexus Tool 2.0

The WEF Nexus Tool 2.0 serves as a common platform that brings together scientific know-how and policy input in an effort to identify current and anticipated bottlenecks in resource allocation trends, while highlighting possible trade-offs and opportunities to overcome resource stress challenges (Daher and Mohtar, 2015). The tool is scenario-based and attempts to explicitly quantify the interconnections between different resources, while capturing the effects of population growth, changing economies and policies, climate change and other stresses. The WEF Nexus Tool 2.0 enables users to visualize and compare the resource requirements of their scenarios and calculate the 'sustainability index' of each scenario (Ness et al., 2007). The model provides the user with the ability to create scenarios for a given country by defining the inputs such as:

(a) Food portfolio: identifying local food production levels versus imports, and technologies in agricultural production;
(b) Water portfolio: identifying different sources of water and amounts needed;
(c) Energy portfolio: identifying sources of energy for water, and energy for agricultural production.

Even though the water-energy-food framework is generic, scenarios created by the tool are site-specific and defined by the local characteristics of the area of study. These may include local yields of food products, water and energy availability and requirements, available technologies and land requirements. The characteristics are defined by the user and allow for the creation of country-specific profiles.

2.2.4.2 Climate, Land-use, Energy and Water Systems models

The Climate, Land (Food), Energy and Water systems (CLEWs) approach focuses on assessing interlinkages between resource systems in order to understand how these are related with each other, where pressure points exist, and how to minimize trade-offs while potentiating synergies (Ferroukhi et al., 2015; IRENA, 2015). This type of integrated assessments usually involves a strong quantification process which can be performed at different scales of complexity: a) by the use of accounting frameworks; b) via the development of sectoral models (for water, energy and land use) and subsequent soft-linking of tools in an iterative process; or c) by making using of one single modelling tool that accounts for the representation of several cross- and inter-systems interactions. The models are then used to investigate questions related to the relevant nexus interactions. The framework is applicable to different geographical scales, from global to regional, national and urban levels.

2.2.4.3 Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism

Multi-Scale Integrated Assessment of Society and Ecosystem Metabolism (MuSIASEM) is an innovative approach to accounting that integrates quantitative information generated by distinct types of conventional models based on different dimensions and scales of analysis (Giampietro et al., 2009). It has proven extremely useful in the characterization of the metabolic pattern of social systems. In MuSIASEM, fund elements are those elements of the observed system that are transformative agents expressing the functions required by society.

In order to bridge the socio-economic and ecological view, MuSIASEM uses simultaneously two complementing but non-equivalent definitions of fund elements, one relevant for socio-economic analysis (human activity and power capacity/technology) and one relevant for ecological analysis (land uses / land covers, water funds), at all levels and scales considered (e.g. local crop field, watershed, whole country). In this way, it provides an integrated characterization of society's metabolic pattern and its effect on the metabolism of the embedding ecosystems by combining non-equivalent systems of accounting.

2.2.4.4 Quantitative Assessment Framework for Water, Energy and Food Nexus

This proposed approach allows integrated quantitative assessments by considering all the WEF inter-sectoral linkages and the competing demand for WEF resources to evaluate future development scenarios (Karnib, 2017). The water, energy and food sectors are interdependent while each faces their own specific supply risks in the face of increases in demand driven by population growth and mobility, climate change, urbanization, economic development, international trade and technological changes (Karnib, 2017). Decision-makers need holistic approaches in order to be better informed about the trade-offs and synergies between the various development and management options, and to help them identify choices on how to manage and plan these resources in a sustainable manner (Hoff, 2011).

2.2.4.5 Analytical Livelihoods Framework

The Analytical Livelihoods Framework (ALF) is the second analytical framework that will be used in this project and forms part of the quantitative component. The ALF was developed by defining indicators for three resource components with societal impact, namely water, energy and food. This tool assists in integrating the effects of these three resources (Mabhaudhi et al., 2019b), and calculates the selected indicators into a composite score (Nhamo et al., 2019b; 2020a). Each of the resources is characterized using some indicators for both their access and availability. In the current versions of ALF, the water indicators are the description of the availability of water as the proportion of available freshwater resources per capita compared with the water productivity as the value of crops produced per unit of water used, simplified as water availability versus water productivity. For the energy sector, the indicators used are calculated from the proportion of the population with access to electricity that is then compared to the productivity calculated from the energy intensity in terms of primary energy produced and GDP (MJ/GDP). For the food sector at a national level, the indicator is derived from the prevalence of food security in a population (%) compared to the cereal productivity as sustainable agricultural production per unit land area (kg/ha).

WEF nexus models and decision-support tools have been developed at a particular temporal and spatial scale, thus including both time and area/location. WEF nexus data systems need to reflect the site-specificity of the study region and incorporate the key activities taking place to describe the unique challenges being faced between different areas (Jacobs-Mata et al., 2021). In several WEF nexus studies, focus has been placed at the regional or national level; however, there are few studies at the catchment or community level in southern Africa (Mabhaudhi et al., 2016).

The research aim of the project is the application of WEF tools at the provincial (Mpumalanga), municipal (Mbombela) and catchment (Crocodile River) levels in the region managed by the Inkomati-Usuthu Catchment Management Agency (IUCMA). This process will compare and refine the current WEF nexus framework approaches available, which will be achieved by the collection and documentation of provincial, municipal and catchment-specific data to analyse WEF components using the selected analytical frameworks and tools. The applicability of WEF nexus assessment frameworks/models by capturing existing data, calculating the interaction through indices and interpreting the reactions will contextually enhance specific decision-making processes at the different levels. This will lead to the intended purpose of advancing the understanding; information and planning processes that will scientifically support policy development and further facilitate decision-making at operational levels.

Table 2.3 Summary of quantitative WEF tools and models including scale and application method

Tool	Scale		Inputs			Application Method	Output			Users	Authors	Other article
	time & spatial		Water	Food	Energy		Water	Food	Energy			
Optimal Management and Decision-making Model												
Urban agriculture using roof-harvested rainwater & WEF nexus in Australia and Kenya	Urban Catchment	Daily Weekly Monthly	Water supply; Agricultural production; Rainfall; Water evapotrans-piration (field or dam)	Production costs, Temperature data	Urban water use, Wx & pop &	Applies economic analyses and modelling; Deterministic probability statically	MegaL/day; Cost pumping; Household (ML); Turnover city; Purification	Crop model yield; Population (city, Urban)	MegaL/day/person; Cost pumping; Energy used; Turnover city $	Household; City council; Local government; WMA; SANParks; Eskom; Farmers	Agudelo-Vera et al. (2012) Amos et al. (2018).	Kenway et al. (2011) Grimm et al. (2008)
WEF resources												
Climate, Land-use, Energy & Water (CLEW)	Catch-ment, Municipal; Farm	Annual Decade	Water withdrawal at different scales (municipal, Catchment and Farm) Water demand Annual Rainfall	Production costs (Fertilizer, Machinery) Food Consump-tion (Municipal GDP) Population	Power generation and refining Energy UV radiation	Technical and economic parameters of power plants, farming; machinery, water supply chain, desalination terminals; irrigation technologies, fertilizer; production	Water pumped; Different at scales; Rainfall (mm)	Crop yield GDP ration Forestry	Energy for pumping (Catchment; Farm & municipal); Water use for energy production	Farmers; Municipal / household; Catchment management; Nature conservation	Ferroukhi et al. (2015) Mpandeli et al. (2018)	Mannan et al. (2018) Howells et al. (2013) Engström et al. (2017) Sušnik et al. (2018)
Analytical Livelihoods Framework (ALF)	Regional and National	Annual or longer	Available water resources Water productivity of crops	Population with access to power	Food security & Cereal production	Calculation of indices from national level data	Available water as proportion freshwater	Primary energy produced & GDP	Sustainable agricultural productivity per unit land area	Researchers, Government officials at different levels,	Mabhaudhi, et al. (2019b) Nhamo et al. (2020a)	

Tool	Scale		Inputs			Application Method	Output			Users	Authors	Other article
	time & spatial		Water	Food	Energy		Water	Food	Energy			
Free Access Web-Based Tool												
WEF Nexus 2.0 Tool	Country, Catch-ment, Farm	Daily Monthly Annual	Identify different sources of water sources; Groundwater withdrawal; Distillation	Local food production levels versus import; Techno-logies in agricultural crop production	Identify sources energy for water, energy for agricul-tural production	Online tool allows the user to create different scenarios with varying food self-sufficiencies	Water Use & Water pumping requirement (m^3)	Land requirements (ha); Selected crop yield (ton)	Energy requirement (kJ); Energy consumption thru import (kJ); Type of Energy to suite selected scenario	Import and export management; Government Officials Policy and regulation of export and import of agricultural products; Eskom	Daher & Mohtar (2015) Brouwer et al. (2018)	[http://www.wefnexustool.org/user.php;](http://www.wefnexustool.org/user.php) Nhamo et al. (2019b) Sušnik et al. (2018)
Concepts based Method												
WWEF Nexus Framework	Local to regional, national, or global	Daily Monthly Annual Decadal	Surplus or excess sources of water and water resource hotspots	Agricultural resource allocation strategy choices	Energy allocation resources thro supply chain	Define & quantify interconnectivity resources including integrative & holistic management strategies	Cost pumping and supply Purification	Food production yield per sector	Energy generation KJ Irrigation energy	Government at different levels (WEF); Nat resource; Food production; Industries; Eskom	Martinez-Hernandez et al. (2017) Nhamo et al. (2020a)	Mohtar & Daher (2016)

Tool	Scale		Inputs			Application Method	Output			Users	Authors	Other article
	time & spatial		Water	Food	Energy		Water	Food	Energy			
System dynamic model												
Water footprints – WEF nexus, diet/food, virtual water trade, ecological footprint, and water governance	Municipal, catchment And provincial		Water supply withdrawals and storage capacity in different industries; Evaporation; Nature conservation water use & storage; water quality	Agricultural inputs, manufac-turing and processing Rainfall	Energy Production Purifica-tion	Footprint method; LCA; input output analysis (IOA); Scenario-builders, forecasting & back-casting; Analyses interconnections, synergies, trade-offs, bottlenecks between WEF sectors	litres /day Cost pumping Storage and loss (l) Purification (R/l) Harvesting (l)	Cost of production, Crop estimates Yield of different commodities. Evapotranspiration (mm)	Cost of pumping Energy used Turnover city different scales, production and manufacturing of food products	Government at catchment level; Nat resource managers; Agricultural input production farm level ;Food production industries; Eskom	Gupta (2017)	Zhang et al. (2018) Van der Laan et al. (2015) Le Roux et al. (2018)
Optimal Management Method												
Biophysical, economical modelling & WEF nexus systems by reviewing crop modelling, economic models of land use, water quality model	Domestic, Farm, Industrial, Municipal, Catch-ment; High risk, Low Risk	Day, Month, Year, Season	Water for drinking, domestic use; irrigation; industrial processes; Precipitation	land use; Income (rent) & Crops; Water origin; Labour costs	Energy Flow in society	Biophysical, economical modelling & crop modelling, land use, & water quality model; Socio-economic indicators, & workforce evolution	litres /day/person; Cost pumping; Energy used; Turnover city $	Crop estimates Yield; Cost of production	Cost of pumping; Energy used; Turnover city different scales,	Household; Local govt; City council; Local govt; Water Manag Agents (WMA); SANParks; Eskom; Farmers	FAO (2014) Giampietro et al. (2009)	Daher & Mohtar (2015)

A project such as this cannot use all of these models. Therefore a short list was drawn up by considering the scale and terms of application for the Crocodile River Catchment. The top WEF nexus tools selected to be considered in this project are shown in Table 2.4.

Table 2.4 Selected WEF nexus framework tools applicable at provincial, municipal and catchment levels

Method	Geographical scale	Model type	Purpose	Application category	References
Analytical Livelihoods Framework (ALF)	Multi-scales	Integrated model	Trade-off analysis, integrated use	Knowledge generation	Nhamo et al. (2020a&b)
WEF Nexus Tool 2.0	National level	Simulation model	Quantitative assessment and forecast of WEF nexus	Governing	Daher & Mohtar (2015)
WEFO – Water, Energy & Food security nexus Optimization model	Multi-scales	Integrated model	Quantitatively assess the interconnections and trade-offs among resource systems as well as environ-mental effects	Governing	Zarei et al. (2021)
Life Cycle Assessment (LCA) of base crops – Sugarcane & Macadamia	Field and Farm level		Quantitative calculation of water and energy used	Operational	Van der Laan et al. (2015) Le Roux et al. (2018)
Build a new tool	Provincial, municipal and catchment scale	Integrating and consolidating tools using inputs from existing tools	Quantitative assessment of water, energy, food and water footprint indices	Operational and policy	Zarei et al. (2021) Van der Laan et al. (2015) Karim et al. (2021)

2.3 DATA REQUIRED FOR WEF TOOLS

The water, energy and food sectors tend to be managed as three independent ministries in most national governments that Tett (2015) and others describe as ‘silos’. It is reasonable to expect that joint management of these sectors in an integrated fashion would provide new efficiencies and lead to synergistic policy developments in ecosystem services and sustainable development. Cooperative governance could be supported by an integrated information management system that provides data products for all aspects of the WEF nexus. The development of a joint management system could advance integrated governance and management frameworks, such as the WEF nexus, that rely on open access to data and information supporting advisory services and joint planning.

Quantifying the interconnections between the energy, water and food sectors is an initial step toward integrated WEF systems modelling, which will further contribute to robust WEF security management. There is an important need for data that supports efforts to understand system borders and spatial dimensions, along with the origin and fate of WEF commodities as well as cross-sector interactions and interfaces (Endo et al., 2020). A comprehensive set of data are necessary across the full WEF scope as the nexus approach is about widening perspectives to unexplored levels. Data acquisition processes will be outlined and simplified in order to initiate quantitative WEF systems modelling for the Crocodile River Catchment.

The methods listed describe both models and frameworks used to assess the WEF nexus. Each model can be classified into one of the following categories: i) a quantitative analysis mode that quantifies the resource flows without modelling scenarios over temporal scales; ii) a simulation type model that is a single model to simulate various scenarios over a range of time scales; iii) an integrated model as a combination model with both quantitative and scenario functions including water footprint and socio-economic indicators.

WEF nexus models are used for different purposes or applications by different users, so a 'nexus task or challenge level' is included in the summary together with the geographic scale and model type information. The three identified generalized purposes are for: a) knowledge generation about the WEF nexus where the data demonstrates linkages and identifies problems, risks or opportunities in the system; b) governance of the WEF components in the system for the purpose of providing guidance at institutional and/or policy level; and c) to support management decisions with the WEF nexus with the purpose to guide technical interventions and/or policy to improve efficiency or effectiveness of resource use.

2.3.1 Currently available WEF nexus data for the catchment

Decisions based on nexus-wide considerations rather than individual elements are likely to produce better if not more informed outcomes (McCarl et al., 2017a). Yet to achieve and capitalize on a better understanding of the relationships among nexus elements, data covering the full nexus scope is needed for the Crocodile River Catchment. A further complication is that data need to reflect changes over time. Desirable types of nexus data include items describing the following:

Currently available GIS data:

- Discharge daily values
- Water balance – catchment level
- Access to improved drinking water (1970-2008)
- Daily precipitation from weather station data
- Rainfall monthly data (2007-2015)
- Daily and hourly sunshine data
- Crop production (tonnes; 1961-2009)
- Production by commodities (nuts, sugarcane, fruits, potatoes, wheat, maize, cassava, groundnuts, millets, rice, sorghum, roots, tubers)
- Livestock production at an aggregate level
- Quaternary catchment grip data

Currently available climate data:

There are several sources of climate data for this catchment but they are in different formats and states of verification. Some datasets are observed or measured data on a daily time step, while others have already been compiled into a daily, weekly or monthly surface on a map. So the climate data to be used will depend on what is needed by the specific application.

2.3.2 Other available data

Data collected for this project has been a continuous consultative process with stakeholders in all three WEF nexus sectors. A number of private and public organizations were consulted to request access to their valuable datasets. Data already obtained from the agricultural sector includes that directly linked to macadamia nuts and sugarcane production and processing. Morokong et al. (2016) indicated that registered agricultural water users and the urban and industrial sectors combined consume 63% and 25% respectively.

2.3.2.1 The water sector

In the water sector, the data acquired first was climate data from the Agricultural Research Council Agrometeorology Climate Databank (Table 2.5). Daily values of precipitation, maximum and minimum temperature and A-Pan evaporation and total solar radiation values were extracted.

Table 2.5 A list of weather stations and available data from start to end (ARC Agrometeorology Climate Databank Moeletsi et al., 2022)

Station Name	Start Date	End Date	Length (y)
Malelane Vergelegen	1966/11/01	2001/03/31	34.3
Komatipoort; Coopersdal	1977/06/01	2002/05/31	24.9
Barberton Senteeko	1979/10/01	2005/01/31	24.2
Nelspruit: NISSV	1905/07/01	2000/05/31	94.6
Mzinti	1997/01/01	Current	24.0
Krokodilbrug	1999/05/01	Current	21.5
Nelspruit	2000/04/01	Current	20.6
Mhlati	2000/01/01	Current	21.0
Komatipoort; Amanxala	2000/06/01	Current	20.5
Eerstegeluk	2010/10/01	Current	10.2

A large amount of information is available at IUCMA including daily rainfall, water supplied to agriculture, municipality and industry for the period from 2000 to 2020. Catchment level water discharge data from major dams in the catchment (Nooitgedacht Dam, Vygeboom Dam, DaGama Dam, Witklip Dam and Kwena Dam) is available. Water allocation information for selected farms and industries is stored by IUCMA for the period 2010 to 2020.

2.3.2.2 The energy sector

The available energy sector data is from the three selected power stations, namely Arnot, Hendrina and Komati. Information related to power generation from 2000 to 2020 was captured, including turbine water use per day (ML), monthly electricity production and total number of staff employed (see Table 3.1). Coal plays a major role in the energy sector in South Africa. Water and employment information about coal mining companies supplying the three selected power stations has been captured. This includes total monthly water use for washing and drilling during coal mining, total monthly electricity at the selected mines and total number of staff employed.

2.3.2.3 The food sector

Water used in irrigated agriculture must not be left out when collecting data for the WEF nexus assessment. The period of observation for irrigated water use was set from 2000 to 2020. Monthly water use in the sugarcane and macadamia nut industries from three of the top growers – Crookes Brothers Ltd (https://www.cbl.co.za/), Kudu & Esperia Farms (https://ivorymacs.co.za/) and Elphick TF and Sons (Pty) Ltd – has been collected together with the annual total area planted.

The energy, water and by-products of sugarcane milling is compiled from one major milling company in Mpumalanga – RCL Foods Sugar and Milling (Pty) Ltd (https://rclfoods.com/) – giving the following information: water and energy used in the milling and refining process, and total number of employees (see Table 4.1). RCL Foods is a member of the South African Sugar Millers Association which represents the interest of all 14 of the sugar millers and refiners in South Africa.

Information about the energy, water and by-products of Macadamia nut production is compiled from three major farms in the catchment – Kudu & Esperia Farms (https://ivorymacs.co.za/), Golden Macadamia (http://www.goldenmacadamias.com/) and Sabie Valley Macadamia (Pty) Ltd (https://valleymacs.co.za/). Information on the total water used for growing and processing the nuts, total energy for processing and irrigation, and total labour for growing and processing was compiled for the period 2000 to 2020.

2.3.3 Data collection challenges

The challenges encountered during data collection vary from sector to sector. Some of the challenges encountered in this study include private companies' data disclosure policies to third parties, and privacy and security considerations by private companies. Another aspect is that data collection and capturing is not a major core business function of many farming enterprises so there is a lack of quality assurance processes. Once the data is obtained for the project, then there are issues of changes in definitions and/or policies which result in questions about data comparability. In addition, the sale of data by government companies is also becoming a serious concern for many researchers.

2.3.4 Managing missing data

The problem of missing data is relatively common in almost all research and can have a significant effect on the conclusions that can be drawn from the data (Graham, 2009). Missing data presents various problems. Firstly, the absence of data reduces statistical power, which refers to the probability that the normal statistical tests will reject the null hypothesis when it is false. Secondly, the lost data can cause bias in the estimation of parameters. Thirdly, it can reduce the representativeness of the samples. Finally, it can complicate the analysis of the study. Each of these distortions may threaten the validity of the analysis and can lead to invalid conclusions. Therefore, this section on managing missing data will be expanded as the current datasets are used in the selected WEF nexus models.

Patching of climate data has been used for many years, so this experience can assist in selecting methods to use in patching missing data in the other datasets. Several different methods are used for patching and infilling climate data, namely the nearest neighbour by distance or by correlation, normal ratio, multiple regression, weighted inverse distance and/or means or weighted averages of selected stations (Bennett et al., 2007; Shabalala et al., 2019). Alternatively, interpolated surfaces can be used with various smoothing techniques or kriging to produce a gridded surface for the various parameters (Jeffrey et al., 2001). The best practice methods used for the southern African semi-arid regions will be used in this project to formulate such surfaces. Some of these methods will then be tested for the parameters from other sectors at various time and geographical scales according to the applicable information.

2.3.5 Metadata and data documentation

As this is a trans-disciplinary project, a mixed method approach will be used. Therefore, qualitative and quantitative data, primary and secondary, as well as observational, simulation and compiled data will all be utilized as inputs and outputs for the models and dissemination purposes. So the principle of "all is data" is used from Grounded Theory (Glaser, 2007). 'Data' can mean many different things, and there are many ways to classify data. Two of the more common data classifications are primary or secondary data, and qualitative or quantitative data. Primary data is data that one collects or generates oneself, whilst secondary data is data that has already been collected through primary sources and made readily available for researchers to use for their own research. Primary data sources may include text, images, video, sound recordings, observations, etc. (Sutton and Austin, 2015). Qualitative data is non-numerical in nature and is often collected through methods of observations, one-to-one interviews, and conducting focus groups surveys and/or experiments. Quantitative data refers to numerical data (Matthews and Ross, 2010). To ensure that data can be understood, interpreted and used, one requires clear and detailed data documentation. Sharing data for long-lasting usability would be impossible without detailed documentation about the data, also known as metadata (Kemp et al., 2018). Detailed metadata must be provided for all data stored in WEF nexus databases. This will include unique resource identifiers (e.g. source, references, contact persons), as well as the methods used to record the data and the quality and completeness of the data. Metadata helps to provide and map interconnections between data and balance consistency and flexibility (Kemp et al., 2018).

There are typically five main categories that data can be sorted into for management purposes:

1) Observational data – data captured in real-time that cannot be reproduced or recaptured (e.g. sensor readings, telemetry, survey results, images, human observation).
2) Experimental data – data from lab equipment and/or under controlled conditions (e.g. gene sequences, chromatograms, magnetic field readings).
3) Simulation data – generated from test models studying actual or theoretical systems. Models and metadata where the input is as important as the output data (e.g. climate models, economic models, systems engineering).
4) Derived or compiled data – the results of data analysis or aggregated from multiple sources can be reproducible although the process can be costly (e.g. text and data mining, 3D models).
5) Reference or canonical data – usually peer-reviewed and often published, fixed or organic collection datasets (e.g. gene sequence databanks, census data, chemical structures).

The category that one chooses will then affect the choices one makes throughout the rest of the data management plan.

This project needs to link the ideas and actions of numerous stakeholders from various sectors. Different datasets at temporal and spatial scales, including vertical and horizontal dimensions, will be analysed for the inclusion into selected WEF nexus models. To be able to perform these tasks, datasets are grouped in logical groups, for example: a) Environmental governance, science in/for society, and co-design/co-production strategies emphasizing the integration of local-national scale stakeholders, and regional scale stakeholders; b) Biophysical measurements and analyses using geophysical, hydrologic and ecological datasets (Endo et al., 2015). In this way, the data becomes more useful as there is an extensive background description provided in the metadata on the "data about the data". The metadata provides the details behind the actual data points and can help to explain variations between different datasets that appear to be similar on the surface. For example, one knows that different instruments measure temperature, but they may give a slightly different absolute value despite being in a similar position. This could be explained by the information provided in a metadata repository. Although one strives to collect and accumulate the most accurate data as possible, sometimes it does not meet some models' stringent requirements. When one links all the pieces of the puzzle together, one can see the whole picture, so the quality of the input data also affects the results obtained.

2.3.6 Data sources for water usage in energy production

Water is indispensable for the production, distribution and use of energy. Chang et al. (2016) explains how the water footprint (WF) of power plants can be used to determine water needed to generate energy (m^3/GWh) by their thermal efficiency, their heat sink accessibility and the cooling systems adopted (Table 2.6).

Table 2.6 Data sources for water consumption of different energy technologies and other manufacturing industries (adapted from Chang et al., 2016)

Energy Type	Production Type	Data Source	Contact	Literature Source
Coal	Surface mining	Barberton Mine	Nomfundo Mdluli	Dai et al. (2018)
		Barbrook Mine	Trevor Cronnright	
	Underground mining	Assmang Chrome	Willie Coetzer	Chang et al. (2016)
		Eskom	Lwandle Mqadi	
Biofuel	Sugarcane (ethanol)	Eco-Gain Consulting	Marianté Herbst	Huang et al. (2020)
		Malelane Cane Growers Association	Aluyn v Graan	
	Maize (ethanol)	RCL Foods	Greg Beyers	Agudelo-Vera et al. (2012)
		AgriSA	Nic Opperman	

Energy Type	Production Type	Data Source	Contact	Literature Source
	Soybean (biodiesel)	Agri Mpumalanga	Gert Smith	Engström et al. (2017)
		Transvaal Agricultural Union of SA	Louis Meintjies	
Natural gas	Conventional Natural Gas	Mpumalanga Dept. Mineral Resources	Deon du Plessis	FAO (2014, 2020)
		SASOL	Martin Ginster	
Solar	Solar Power	Aurecon	Johnny Beumer	Zhang et al. (2019b)
		Eskom	Danisa Malope	
Wind	On/Offshore	Coastal Fuels	Willem Potgieter	Howells et al. (2013)
		Dept. Energy	Muzi Mkhize	
Manufacturing	Wood & pulp & paper	Sappi, Mondi	Benjamin Olivier, Murendeni Makhado, Ernst Deichmann	
	Steel	Columbus Stainless		
	chemicals	ChemiCorp, NutrorChem		
Construction		York Timbers, Murray & Roberts, Kentz,		
Tourism		SANParks, SANBI, MP Tourism & Parks Agency	Eddie Riddell; Andre Beetge; Anton Linstrom	

2.3.7 *Data sources all along the food value chain*

The continuously increasing world population drives the increasing food demand. The water-food nexus must account for green, blue and grey water consumption used during the cultivation, processing and marketing along the value chain to the garbage disposal of food scraps and losses. The water-food nexus mainly refers to the water used for production of food or agricultural produce (e.g. cereals, vegetables, fruits, edible oils), animal products (e.g. meat, eggs, fish), and for food and beverage production (e.g. soft drinks, tea, coffee). The necessary information must be collected from across the agricultural and food processing sectors (Table 2.7).

Table 2.7 Data sources for water consumption (m^3/kg) of main food products (correct as at 2020)

Food Items	Food Products	Data Source	Contact	Literature Sources
Cereals	Wheat	Agri Mpumalanga	Gert Smith	Nhamo et al. (2016) Zhang et al. (2018)
		AFRIFORUM NST	Christo Peyper	
	Maize	AgriSA	Nic Opperman	
		DARDLEA	Dr Kgaphola	
	Sorghum	Transvaal Agricultural Union of SA	Louis Meintjies	
		AgriSA	Nic Opperman	
	Barley	AgriSA	Nic Opperman	
		Eco-Gain Consulting	Marianté Herbst	
Industrial crops	Tobacco	AgriSA	Nic Opperman	Nhamo et al. (2016) FAO (2014, 2020)
		Eco-Gain Consulting	Marianté Herbst	
	Cannabis	Transvaal Agricultural Union of SA	Louis Meintjies	
		Eco-Gain Consulting	Marianté Herbst	
	Hemp	Transvaal Agricultural Union of SA	Louis Meintjies	
		AgriSA	Nic Opperman	
	Cotton	AgriSA	Nic Opperman	
		Transvaal Agricultural Union of SA	Louis Meintjies	

Food Items	Food Products	Data Source	Contact	Literature Sources
	Sugarcane	Malelane Cane Growers Association	Aluyn v Graan	
		SASRI	Abraham Singels	
Animal Products	Beef	Transvaal Agricultural Union of SA	Louis Meintjies	Gerbens-Leenes et at. (2013)
		RCL Foods	Greg Beyers	
	Pork	Transvaal Agricultural Union of SA	Louis Meintjies	
		AFRIFORUM NST	Christo Peyper	
	Chicken Meat	AgriSA	Nic Opperman	
		Suidkaap Farmers Association	Philip Daniel	
	Mutton	AgriSA	Nic Opperman	
		AFRIFORUM NST	Christo Peyper	
	Goat Meat	NAFU	Joe Gondo	
		Eco-Gain Consulting	Marianté Herbst	
	Eggs	RCL Foods	Greg Beyers	
		Transvaal Agricultural Union of SA	Louis Meintjies	
	Milk	RCL Foods	Greg Beyers	
		NAFU	Joe Gondo	
Vegetables	Potatoes	AgriSA	Nic Opperman	Nhamo et al. (2016) FAO (2014, 2020)
		Suidkaap Farmers Association	Philip Daniel	
	Onions	AGRI SA	Nic Opperman	
		Transvaal Agricultural Union	Louis Meintjies	
	Carrots	AGRI SA	Nic Opperman	
		Transvaal Agricultural Union	Louis Meintjies	
	Tomatoes	AgriSA	Nic Opperman	
		Transvaal Agricultural Union	Louis Meintjies	
Fruits	Citrus	Subtrop	Barry Christie	Zhang et al. (2018)
		Jab Dried Fruits	Martin Janson	
	Subtropical fruit	Subtrop	Barry Christie	
		Jab Dried Fruits	Martin Janson	
Nuts	Pecan nuts	Agri Mpumalanga	Gert Smith	Engström et al. (2017)
		Eco-Gain Consulting	Marianté Herbst	
	Macadamia nuts	Agri Mpumalanga	Gert Smith	
		Mondipak	Ernst Deichmann	
	Canola	Aurecon	Johnny Beumer	
		RCL Foods	Nico Stolz	
Oil Seeds	Sunflower	Aurecon	Nico Stolz	Engström et al. (2017)
		RCL Foods	Greg Beyers	
	Soybean	Aurecon	Johnny Beumer	
		DARDLEA	Dr Kgaphola	
	Groundnuts	Aurecon	Johnny Beumer	
		AFRIFORUM NST	Christo Peyper	
	Wine	RCL Foods	Greg Beyers	
		Suidkaap Farmers Association	Philip Daniel	
Beverage Products	Tea	Suidkaap Farmers Association	Philip Daniel	Ercin et al. (2011)
		DARDLEA	Dr Kgaphola	
	Soft drinks	Subtrop	Barry Christie	
		Suidkaap Farmers Association	Philip Daniel	
Food	Processing & packaging	Tiger Brands, Pioneer Foods, Tongaat-Hullett, Astral		
Retail sector	Supermarket chains	Checkers, Pick n Pay, Spar		

2.3.8 Data sources for natural and population resources and other water usage

In order for the WEF nexus tools to be in operational mode, one also needs other information about water and energy that can be derived from the natural resources information for the whole catchment. This information can be used as the input to account for the supply or availability of water and solar energy and the conditions conducive for the cultivation of the food crops. In addition, information about population distribution, employment and unemployment information and transport will have an influence on the water and energy consumption by households. According to which of the WEF nexus models or tools to be used, such information is also required (Table 2.8).

Table 2.8 Data sources for calculation of water consumption from secondary datasets

Resources Parameter	Data Source	Contact
Climate, pollution & soil data	ARC-NRE	Chris Kaempffer
	SAWS	Charlotte McBride
	DWS	Eustathia Bofilatos
	UKZN-CWRR	David Clark
	CSIR	Rebecca Garland
Water flow	DWS	Eustathia Bofilatos
	IUCMA	Senzo Mduduzi Lukhele
	HydroLogic	Leanne Reichard
Population & demographics	StatsSA	
	Employment in each sector	
Transport	Google maps	
	Dept. Public Works, Roads & Transport; TRAC	Freight databank; Reggy Nkosi
Policy	Water	Level – National & Provincial & Municipal / Sector / Community
	Energy	
	Environment	
	Food	

As there are already existing databases and data platforms being used by the Inkomati-Usuthu Catchment Management Agency (IUCMA), this project leveraged on that information and the database was expanded to accommodate the additional information required by the WEF nexus tools. IUCMA, Mpumalanga provincial government departments and the Mbombela Local Municipality are the primary stakeholders together with Mpumalanga industries.

2.4 THEORETICAL FRAMEWORK FOR STAKEHOLDER ENGAGEMENT

2.4.1 Analytical Framework 1: The ALF tool and its applicability to WEF nexus catchment decision-making

The Analytical Livelihoods Framework (ALF) used in this project forms part of both the quantitative and qualitative components. The ALF was developed by defining indicators for three resource components with societal impact, namely water, energy and food. This tool assists in integrating the effects of these three resources (Mabhaudhi et al., 2019b) and calculates the selected indicators into a composite score (Nhamo et al., 2020a). Each of the resources is characterized using some indicators for both their access and availability. In the current versions of ALF, the water indicators are the description of the availability of water as the proportion of available freshwater resources per capita compared with the water productivity as the value of crops produced per unit of water used, simplified as water availability versus water productivity. For the energy sector, the indicators used are calculated from the proportion of the population with access to electricity which is then compared to the productivity calculated from the energy intensity in terms of primary energy produced and GDP (MJ/GDP). For the food sector at a national level, the indicator is derived from the prevalence of food security in a population (%) compared to cereal productivity as sustainable agricultural production per unit land area (kg/ha).

The results for these indicators are presented in the form of a spider diagram to reveal the relative strengths and weaknesses in each sector, and to give guidance about priority areas where interventions are needed to bring balance and cohesion across the sectors. From this framework, the user can evaluate synergies and trade-offs in resource planning and utilization. The ALF model has established quantitative relationships across the WEF sectors, simplifying the interlinkages among resources, by using relative indicators for an area or location being analysed. It has been applied at a national level for South Africa as a case study but needs to be adapted for other scales and periods as defined by the user (Nhamo et al., 2020b).

When considering the Sustainable Development Goals, Mabhaudhi et al. (2021&2019b) state that the ALF is one of the tools that is used for a WEF nexus analysis as it can be assessed through measurable indicators. This would be an enabler to promote socio-ecological sustainability across the three mentioned sectors. The team developed a facilitative decision-making process to engage with government officials at different levels on the uptake and use of the ALF in WEF nexus decision-making and policy development. This will be integrated and reported on in subsequent deliverables.

2.4.2 Analytical Framework 2: The Network of Adjacent Action Situations (NAAS) approach

To identify and analyse the key Action Situations (AS), their interactions and outcomes, as well as their underlying factors, the method adopted by Srigiri and Dombrowsky (2021) was followed by using the Network of Adjacent Action Situations (NAAS) approach of McGinnis (2011) as an analytical tool. This approach is an addition to polycentric governance, and argues that with all AS there is almost always a NAAS that has a bearing on the actions of the focal AS. In his description of the NAAS approach, McGinnis (2011) explains that an AS Xi is adjacent to Y if the outcome of Xi directly influences the value of one or more of the working components of Y (Table 2.1). This helps one to see the connections between key WEF decisions and what may lead or contribute to a certain policy implementation scenario.

While in natural resource governance the outcome of the focal action situation is usually physical in nature, in terms of change in quality or quantity of the resource in focus, the outcome of the Adjacent Action Situation (AAS) could be physical or institutional in nature. If the focal AS is the production of food and the action results in a reduction in the quantity and quality of water, then the AAS could be an organizational arrangement where new rules are made regarding restrictions on fertilizer application which will constrain the actions in the focal AS. On the other hand, if the AAS focuses on actions for the production of bioenergy crops or withdrawal of water for thermal power generation, the resulting outcome of that AS would alter the physical working component of the focal AS (Srigiri and Dombrowsky, 2021) (Fig. 2.5).

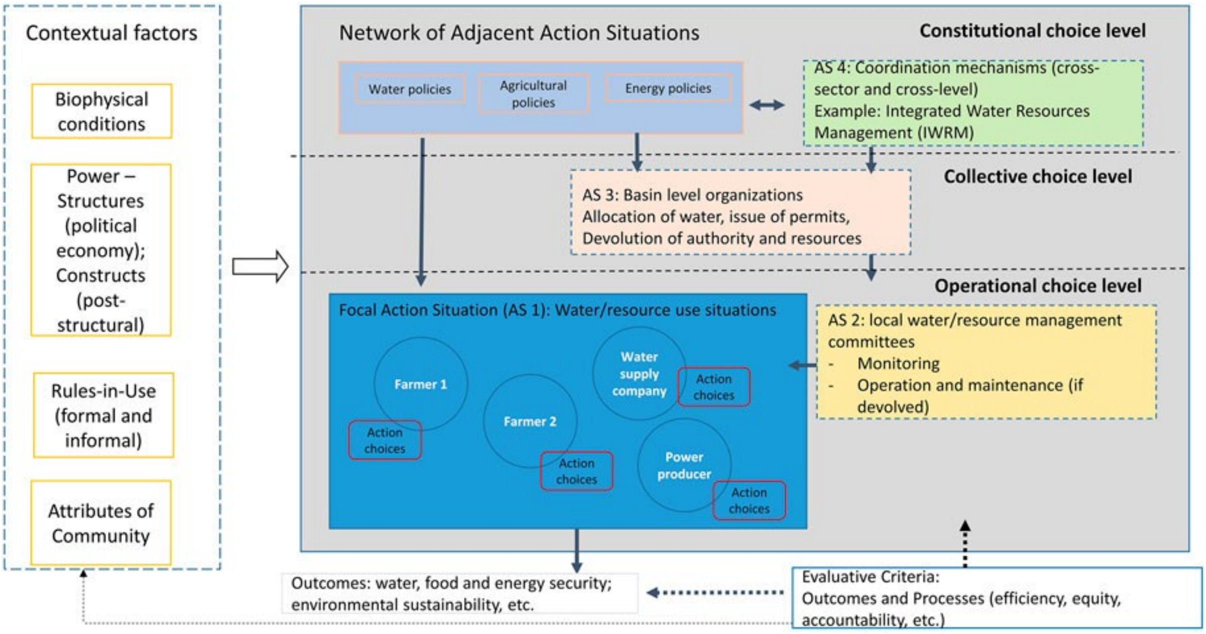


Figure 2.5 WEF nexus governance as a Network of Adjacent Action Situations (NAAS) (adapted from Srigiri and Dombrowsky, 2021; McGinnis, 2011; Ostrom, 1990).

This approach requires coordination among actors, but coordination can take different forms, such as cooperation, coercion and competition. The type of interactions different decision centres engage in to coordinate their transactions is dependent on the way authority, information and resources are distributed. It was further argued that WEF nexus governance requires a combination of different coordination mechanisms to manage the cross-sector and cross-scale interlinkages. The coordination mechanisms of hierarchies, markets and cooperation are further embedded in the social structure or relationships, which facilitate or constrain coordination (Srigiri and Dombrowsky, 2021).

2.4.3 A transdisciplinary approach for stakeholder engagement in the WEF nexus

Daher et al. (2017) suggest that seven essential questions should be asked to select or develop the most appropriate modelling approach for each specific WEF nexus case:

1) What is the critical development question in the specific study?
2) Who are the players/stakeholders?
3) At what scale?
4) How is the system of systems defined?
5) What do we want to assess?
6) What data is needed?
7) How do we communicate it?
8) Where do we involve the decision-maker in the process?

Data collected for this project has been a continuous consultative process with stakeholders in all three WEF nexus sectors (Fig. 2.6). Semi-structured interviews are the principal method for case-study development and answering the above questions, and were conducted with key stakeholders on three separate occasions. Several private and public organizations were consulted to request access to their valuable datasets. Secondary data obtained from the agricultural sector includes data that is directly linked to macadamia nuts and sugarcane production and processing. A large amount of information was sourced from the IUCMA including daily rainfall, water supplied to agriculture, municipality and industry for the period from 2000 to 2020, catchment level water discharge data from major dams in the catchment and water allocation information for selected farms and industries. Data was also sourced from Statistics South Africa (StatsSA), mainly the agricultural census done in 2011 and 2017, General

Household Survey, the quarterly labour force survey, the World Bank database and other databases. The team also used secondary data and conducted stakeholder workshops, scenario development workshops and scenario validation workshops.

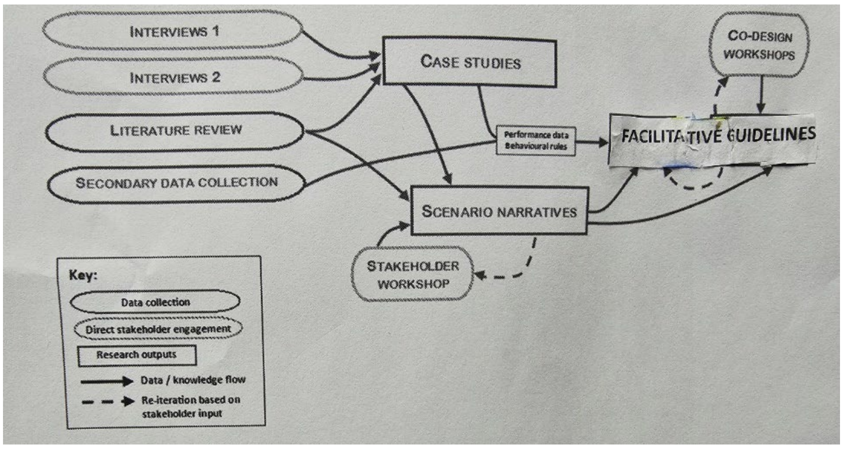


Figure 2.6 Data collected as a continuous consultative process with stakeholders (adapted from Hoolohan et al., 2018).

The project team opted for a participatory scenario development approach to engage with different sub-catchments of the IUWMA on WEF nexus development trade-offs. This was done through a multi-stakeholder workshop with participation from government officials, parastatals and the private sector. Stakeholders from diverse backgrounds attended with representatives from agriculture, education, environment, water, sanitation and private sector industries. This qualitative and participatory technique was meant to encourage discussion, deliberation and the exchange of ideas. The process identified different views on the issues and actions available drawing on stakeholders' views, experiences and resources. During the discussion, the framing and re-framing of perceptions and conceptions of problems were facilitated, resulting ultimately in greater social learning (Patel et al., 2007).

The team also conducted two focus group discussion (FGD) engagements with stakeholders from the IUCMA and Mbombela Local Municipality (LM). One FGD involved a management group of IUCMA individuals around the various decision structures involved in the distribution and/or development of WEF nexus policies. Participants included high-level senior staff from the hydrology unit and staff from the institution and participation division. The second FGD was held with officials from the Mbombela LM, from the Environmental Management and Planning Department. The FGD mechanism was mainly an interactive exercise allowing participants to share their perceptions on factors influencing their decision-making (within their organization and also as individuals), providing a definition of the WEF nexus and how it influences their day-to-day decision-making, planning, design and implementation. The team also conducted a validation workshop with participants from Water Irrigation boards, IUCMA, provincial departments and developmental partners. The team went through the scenarios that were developed during the first stakeholder workshop and were adjusted accordingly. The team was also involved in developing facilitative guidelines for water demand allocation, particularly for the agricultural industry. This will assist the IUCMA and other agricultural stakeholders in decision-making and policy formulation.

CHAPTER 3: OVERVIEW OF THE CASE STUDY AREA

3.1 INKOMATI-USUTHU WATER MANAGEMENT AREA AND CROCODILE RIVER CATCHMENT CONTEXT

The Inkomati-Usuthu Catchment is situated in the eastern part of South Africa mainly in the Mpumalanga Province ranging from the Highveld where the rivers start and stretching into the Lowveld and the borders with Mozambique and Eswatini (Fig. 3.1). The Inkomati-Usuthu Water Management Area (IUWMA) comprises the following river basins: Sand River, Sabie River, Crocodile River (east), Komati and Lomati rivers, as well as the Usuthu River. The IUWMA, like virtually all WMAs in South Africa, is vulnerable to the negative impacts of global climate change and is already struggling with food and water insecurity. Various national development and growth strategies have outlined several cross-sectoral development pathways that have direct impacts on water, energy or agriculture. In terms of agriculture, the IUWMA has committed to increasing the contribution of agriculture to economic development, supporting both food security and exports; to reduce poverty; to increase food and nutrition security through sustainable use of natural resources; improved access to markets; and improved disaster and risk management systems. Possible interventions to achieve this include conservation tillage, crop diversification, regenerative farming, hydroponics, livestock selective breeding, micro-irrigation, organic farming and solar dryers. Finally, in terms of energy, the aim is to implement small-scale, decentralized renewable energy technologies to improve energy access in rural areas and reduce unsustainable wood harvesting practices; and to increase the use of grid-connected renewable technologies with fuel sources such as waste, solar, bagasse (from the sugar industry) and wood chips.

3.2 BIOPHYSICAL CONTEXT

The Crocodile River is one of the most important rivers in South Africa due to the broad range of riverine habitats, ranging from cold mountain streams in the Drakensberg to slow-flowing temperate waters where the river meanders through the Lowveld. The IUWMA has a catchment size of 28 757 km^2 (McLoughlin et al., 2021). The Crocodile River has a total length of 320 km draining a catchment of 10 450 km^2 and rises at an altitude of 2000 m above sea level in the Steenkampsberg mountains near Dullstroom (Kleynhans et al., 2013). The river then flows into the Kwena Dam and eastwards through Mbombela, eventually joining the Komati River before entering Mozambique near the Lebombo border post. The Elands River and Kaap River are two large tributaries of the Crocodile River system. The Elands River originates near the Elandsfontein road turn-off from the R540 in the highlands (near Groenvlei colliery) and joining the Crocodile River near the junction of the N4 and R539 roads. The Kaap River joins the Crocodile lower in the catchment between Mbombela and Malelane, near the junction of the N4 and R36. The other smaller tributaries of the Crocodile River include the Lunsklip, Nels, Houtbosloop, Gladdespruit, White (Wit) and Besterspruit rivers. The significant dams include the Kwena Dam, Ngodwana Dam, Witklip Dam, Klipkoppie Dam, Longmere Dam and Primkop Dam. Consumptive water uses associated with the Crocodile River include industry, irrigated agriculture and domestic water supply (McLoughlin et al., 2021).

Mpumalanga Province has a population of about 4 400 000 people (in 2017, StatsSA, 2020). There has been about a 1% growth in the population every year shown by values of 4 039 939 in 2011, 4 400 000 in 2016 and an estimated 4 743 584 by 2021 (StatsSA, 2020). The total area of the province is 76 495 km^2 which means it is the second smallest RSA province after Gauteng (Fig. 3.1), and yet it has the fourth largest economy in the country. Mbombela (Nelspruit) is the capital city of the province and the administrative and business centre of the Lowveld. Other important towns are eMalahleni (Witbank), Standerton, Piet Retief, Malelane, Ermelo, Barberton and Sabie. A major challenge in the catchment is uncontrolled urbanization (City of Mbombela, 2020). In the more recent past, urban migration has been centred on the town, with many nearby rural areas included in the Mbombela LM. A range of land cover is present in the catchment including wetlands, indigenous forests, dense bush, open bush and grasslands. Most land cover is taken up by forest plantations and cultivated lands, which include sugarcane and other annual and perennial crops (Fig. 3.2, 3.3, 3.4 & 3.5). The area covered by the Crocodile River Catchment, including all land cover classes in the Inkomati-Usuthu, is 27 844 km^2.

Figure 3.1 A map of South Africa with its provinces showing Mpumalanga in the north-east of the country (ARC-NRE, 2022).

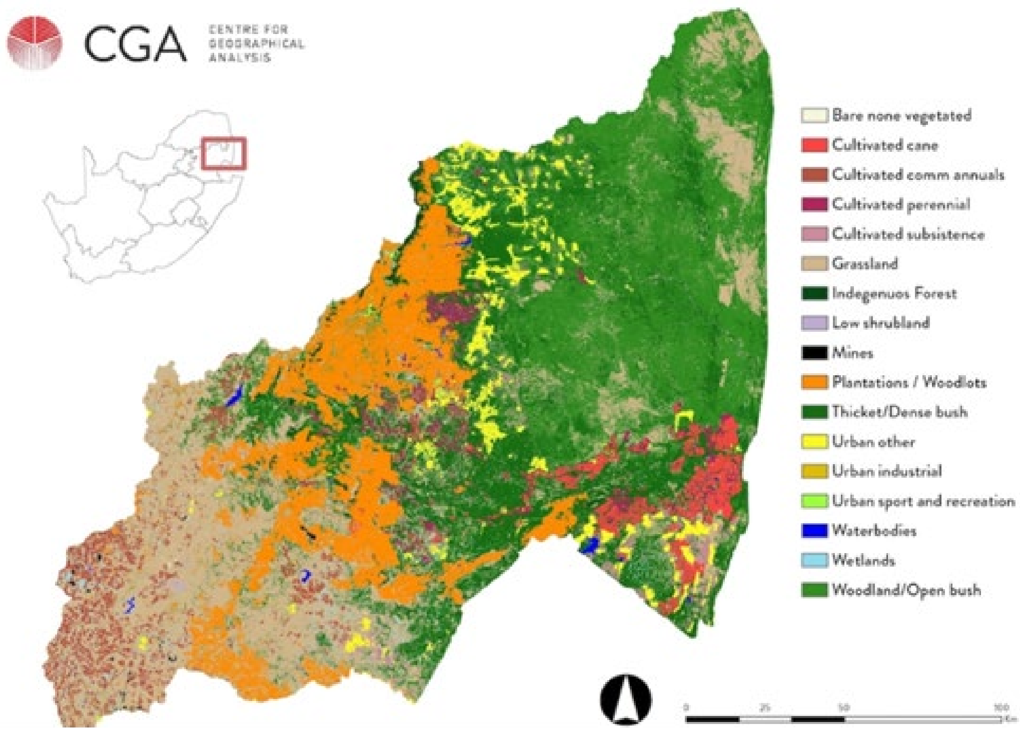


Figure 3.2 Land cover across the Inkomati-Usuthu WMA showing distribution of cultivated lands and plantations, urban areas, and natural vegetation (including grassland, indigenous forest, low shrubland, woodlands / open bush, thickets / dense bush) (CSIR, 2017).

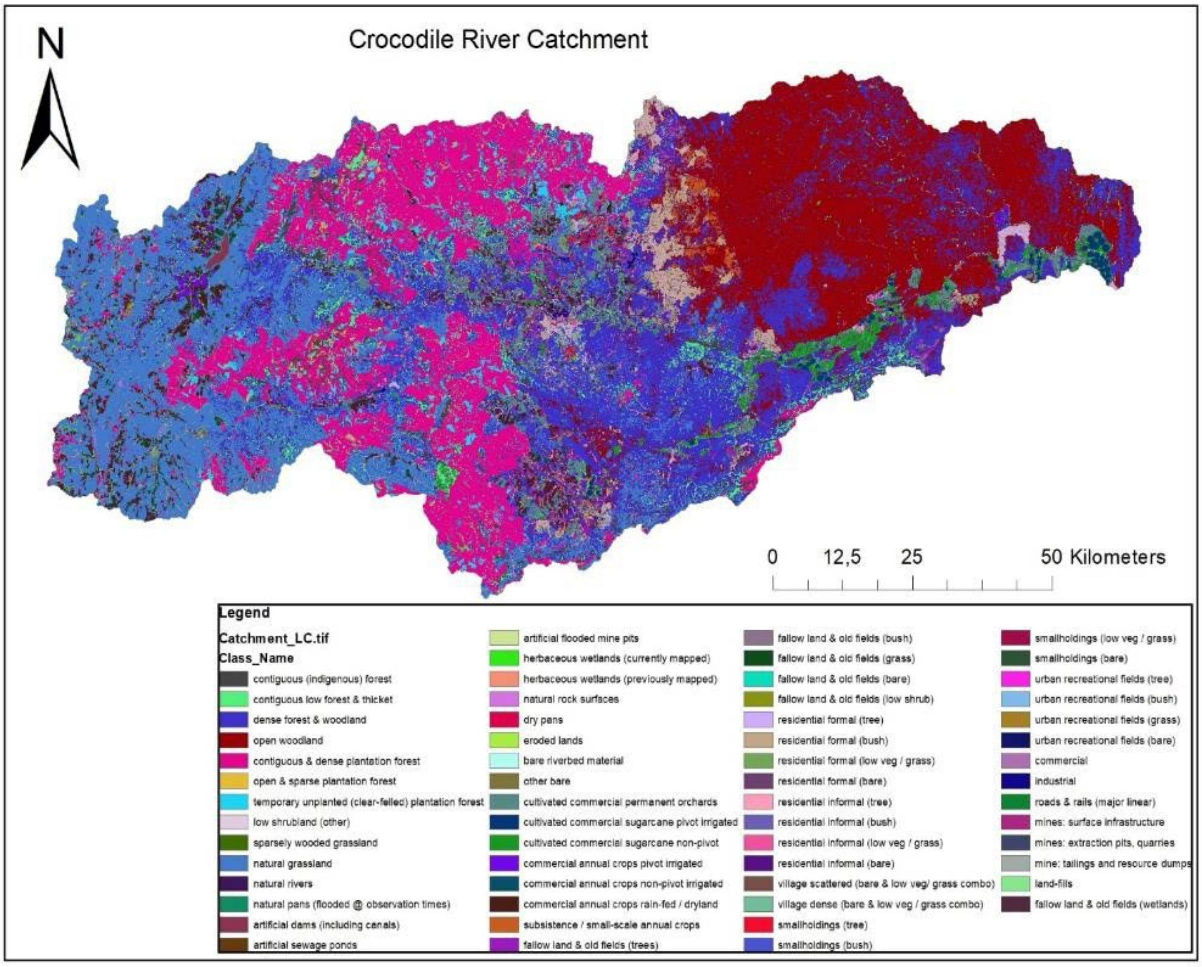


Figure 3.3 Land cover across the Crocodile River Catchment showing industrial development, residential areas, smallholdings, forests, water bodies, fields, mines, roads, cultivated lands and plantations, urban areas, and natural vegetation (including grasslands, indigenous forest, low shrubland, woodlands / open bush, thickets / dense bush) (ARC-NRE, 2022).

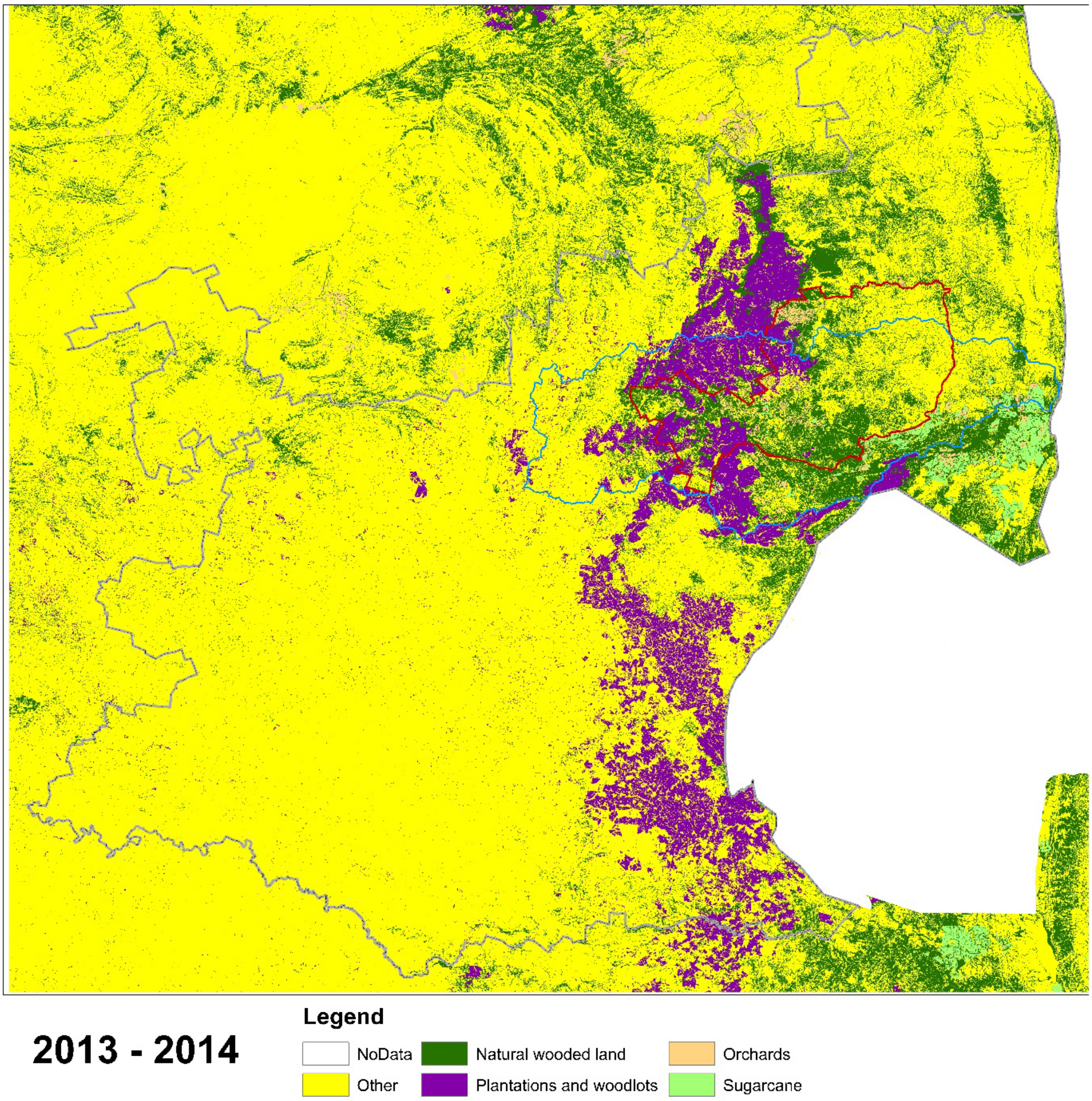


Figure 3.4 Land cover change map of year 2013/2014 with land used mostly for natural wooded land, plantations and woodlots about 10 years ago (ARC-NRE, 2022).

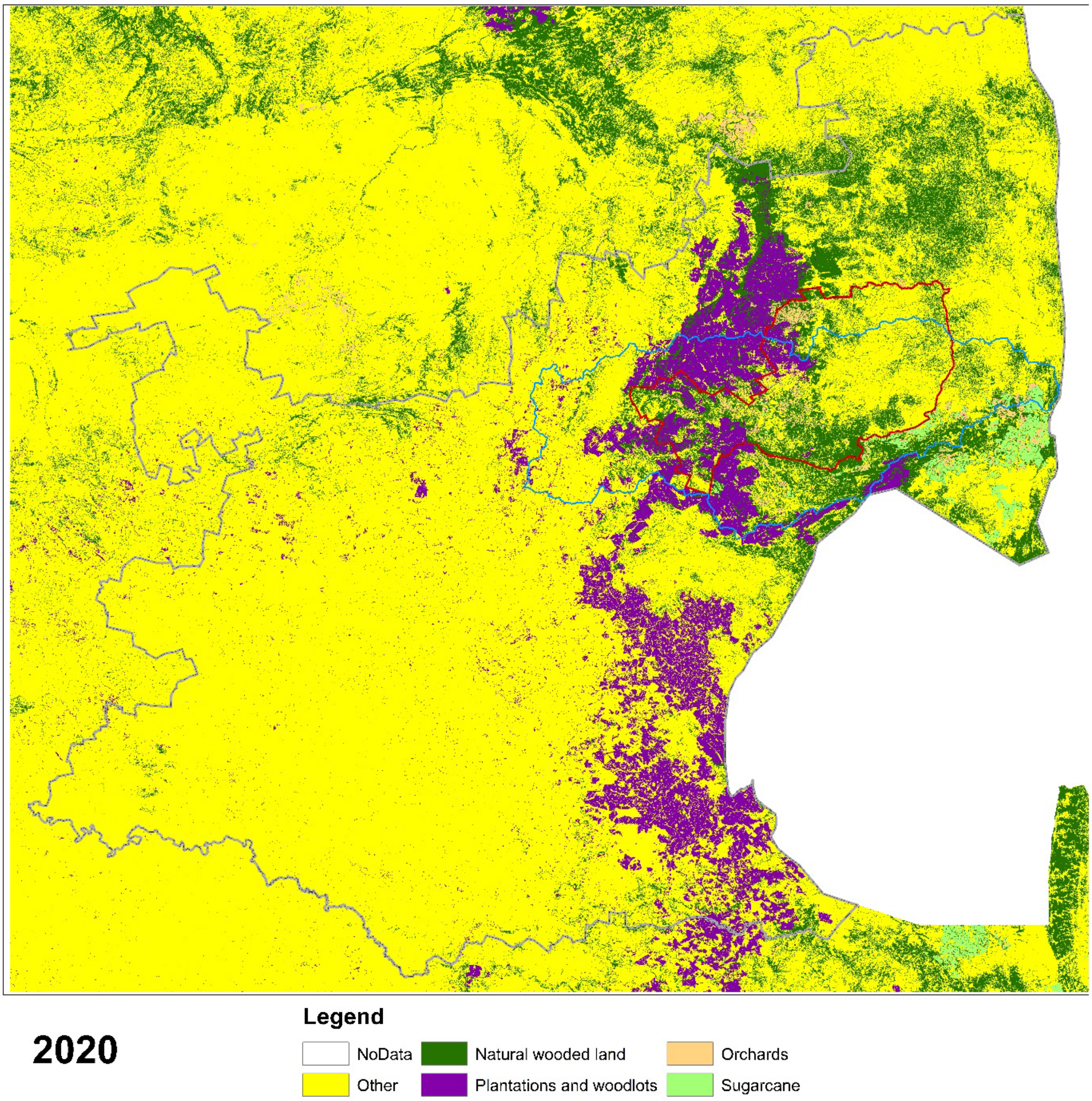


Figure 3.5 Land cover change map for year 2020, showing a reduction in natural wooded land and an increase in other and orchards (ARC-NRE, 2022).

3.2.1 Water sector information

South Africa is a water-scarce country. The national average consumption is around 233 litres capita^{-1} day^{-1} while the estimate for Mpumalanga Province is 205 litres capita^{-1} day^{-1} (Green Cape, 2021). In this province, 91% of households have access to water, mainly through the provision by municipalities in cities and towns such as Mbombela. The mean annual rainfall in the catchment is 800 mm per annum (Bate et al., 1999) depending on the location of the area (lower, upper, west or east), with the west receiving higher rainfall. Simpson et al. (2019) specify that Mpumalanga is characterized by annual rainfall that ranges from 400-600 mm per annum in the north-east and 600-800 mm per annum in the west, while portions of the central zone receive annual rainfall exceeding 1000 mm per annum. McLoughin et al. (2021) state that the mean annual runoff is at 3188 000 Mm^3. The total volume of water allocated for the performance cycle 2019/2020 was 958 419 m^3 annum^{-1} (IUCMA, 2020). The main use of catchment water is for irrigation of crops within the agriculture-food sector, followed by forestry and the ecological reserve. Of the surface water in the province, 75% is utilized for irrigation, 9% is utilized for electricity generation, 9% for mining and bulk industrial users, 9% for afforestation, and 8% for urban water usage (including 3% for rural use) (Simpson et al., 2019). The proportion of water utilized for irrigation in Mpumalanga is less than the average global agricultural water usage, which constitutes ~70% of freshwater supplies (Simpson et al., 2019). The other sectors where the demand for water is increasing include domestic and industrial use which were both less than 5% in 2010. The assurance of supply percentage values shows how the water available will continue to be insufficient to distribute to all the critical sectors as the demand exceeds the supply.

3.2.2 Energy sector information

Most of South Africa's coal-fired power stations are in Mpumalanga Province. RSA produced about 253 TWh of power in 2014, 92% of which was generated using coal (Simpson et al., 2019). There were 583 505 households with access to electricity in the province and 219 375 households had access to free basic electricity in 2008 (DLG, 2009). In 2016, the percentage of households in Mpumalanga that used electricity for cooking was 74.2% (StatsSA, 2016b). The percentage of households connected to the electricity grid increased from 75.9% in 2002 to 87.8% in 2015, which is slightly higher than the national average of 85.5% (StatsSA, 2016b&c). The Mbombela LM reported increases in electricity supply for all periods since 2001. They show that 71 418 (79.8%) households were added to the grid between 2001 and 2011, and by 2016 the number of households with electricity was 190 065. Although much progress has been made, there are other areas that still need electrifying, particularly in rural areas. The municipality, in partnership with Eskom, is upgrading existing power stations to be able to cater to the whole of the municipal area (City of Mbombela, 2020). Thus, the Mbombela State of Electricity Report shows the improvement in the energy supply across the municipality, which stood at 91% of the community in 2016 (City of Mbombela, 2018).

3.2.3 Food sector information

Agriculture was responsible for 3.4% of Mpumalanga's total GDP of ZAR 269 863 million in 2013, which gave a GDP per capita for the province of ZAR 64 910 (OECD Stats, 2018). The sector accounts for 4.3% of the gross geographical product (GGP) of the province and for nearly 12% of employment (StatsSA, 2011). Only about 19% of Mpumalanga's land area is used for agricultural production (Anonymous, 2012) of which Lotter (2015) states about 1 477 934 ha or 19.31% is cultivated land. Crops include maize, wheat, sorghum, barley, sunflower, soybeans, macadamia, groundnut, sugarcane, vegetables, coffee, tea, cotton and tobacco, as well as citrus, tropical, subtropical and deciduous fruits. Fruits (tropical and sub-tropical), nuts and vegetables are major contributors to the provincial and national export basket. There is still scope for expansion in this sector, both in terms of lands planted and downstream beneficiation (Anonymous, 2012). Mbombela LM has in the past devised various means to curb poverty with initiatives such as job creation, support for small agricultural businesses, and implementation of 'Food for Waste' programmes (City of Mbombela, 2020). Food production flourishes when water, energy and land are abundant resources (Lawford, 2019) and is limited when these resources are scarce. Lawford (2019) states that food security is essential to sustain human societies and therefore needs to be promoted. Sectors such as agriculture lost approximately 20% of jobs between the first quarter of 2009 and 2010 (Anonymous, 2011).

3.2.4 Conclusions about biophysical aspects

The WEF nexus application has been applied at Crocodile River Catchment level in order to obtain the synergies and trade-offs to be applied between the three different sectors. From the results discussed, it has been shown that despite Mpumalanga being considered as a developing South African province (relative to Gauteng or the Western Cape), it has an inadequate supply of water that does not meet the increasing demand and has low food insecurity amongst most of the population. However, there are some inconsistencies in the distribution of resources to the critical sectors, which can be addressed by applying similar analysis for an urban area (e.g. Mbombela) and in a smaller catchment area (e.g. Lower Komati).

The water sector is facing the challenge of increased demand from sectors such as mining and industry. Urban development (urbanization) means that more water resources need to be diverted towards household use and human residential developments. The presence of the Crocodile River Catchment has meant that even though South Africa is water scarce, this important resource has been available in Mpumalanga Province for both food production using irrigation and for energy production via coal-fired power stations that require large amounts of water. However, the proportion of water utilized for irrigation in the province is less than the average global agricultural water usage, so the water demands of other sectors such as domestic use are nearly being met. Other water resource information was limited across the catchment and the food production areas, including water quality, so the effect of poor water quality and pollution could not be evaluated during this preliminary study.

The energy sector has contributed to improved livelihoods by supplying almost all domestic requirements, as more households have steadily been electrified. The issue of electricity consumption by the water and food sector is still unclear and seems to be insignificant, but needs clarification in future. The majority of energy in the Crocodile River Catchment is used in the industrial and transport sectors and very little is used for food processing. This is evident from the calculation of the use of only 3.8% of the province's total electricity in the sugar milling/processing industry. The questions surrounding the use of clean and renewable energy are still a challenge as it is developing at a very slow pace. With time, the issue of increasing prices from the main electricity provider in South Africa (Eskom) will become a disadvantage to the consumers who are mostly low-level earners.

The food sector index calculations showed that Mpumalanga is a food-secure province with a low food insecurity index and it would be interesting to compare this with the unemployment rate. However, the agricultural industry sector only contributes low employment volumes that are partly seasonal (e.g. tropical and sub-tropical fruit harvesting) even though the GDP of the province is largely brought in through agricultural produce. The results show a low cultivated proportion of total land, low irrigation levels, and even low energy supply contributing to the production of food in the province. Therefore, there is an opportunity for expansion. This could also mean that the sugar exports may not be beneficial to the communities of Mpumalanga but mainly to the food processing industry. The application of the indices to other agricultural food products by comparison to the base crop of sugar will help the distribution of the resources, by not focusing only on sugar production but to expand the analysis to other food crops such as macadamia nuts, fruits and vegetables.

3.2.5 Recommendations

Engagements with stakeholders to share the information acquired are needed to co-develop future scenarios together. Once the four scenarios are described in more detail, the researchers can propose adjustments to each of the Sustainability Performance Indicators in line with the specific scenario. The SPIs will be compared across the time slots (baseline, centred around 2030 and 2050) with the inputs to describe the changes expected under each scenario (business as usual, political/policy change, socio-economic change, climate change). Much work is still needed on the use of these types of WEF nexus indicators and SPIs in the routine allocation of water by IUCMA. If the index is defined as the 'amount of resource required divided by the allowable capacity or limit', then such an index can give decision-makers an idea of whether the requirement is being met or whether there is a high degree of stress. If one has such indices for various agricultural or river systems and areas, then it will be possible to assign some priorities to the various indices. In this way, the aspects experiencing higher stress can be addressed sooner or given a higher priority when planning.

The further collection and SPI analysis of the necessary data from all three sectors will assist in providing better decision-making in the province in terms of water and energy allocations. This, is turn, will assist in planning for the expansion and development in the agricultural industry for more sustainable food production. As discussed in the WEF approaches, the application of more WEF tools is needed at catchment level, as the available data is mostly only available at national scale. Looking at catchment scale can be limiting, as some of the data is rather old and not current. Application of the tools at other scales can give clearer scenarios than currently provided such as at provincial and municipal levels. The proposed outputs of the project will be guidelines concerning water demand allocations particularly for the agricultural industry. This will assist the IUCMA and other agricultural stakeholders in their decision-making and in policy formulation in line with the Integrated Development Plans.

3.3 POLICY AND INSTITUTIONAL LANDSCAPE FOR MULTI-LEVELS

The policy and regulatory landscape that encompasses the WEF nexus is complex. Even for one component of one of the sectors of the nexus, there are numerous regulations from multiple sources, and many of these regulations and their sources are place and activity specific. This raises an important question: how can we map and design a governance framework to account for all the interactions and interdependencies of the nexus? A similarly complex legal architecture connects the WEF sectors in South Africa. Water security is a priority for both energy and agriculture, although there are differences between them in the priority given to the various means to address it. The legislation also relies on the use of subsidiary regulations, which establish the WEF nexus as a framework for catchment-based assessments frameworks for coordination. The links between the WEF sectors are often more explicit in sectoral policies and strategic plans, but there is also a lack of clarity on the relative hierarchy of various regulations, policies and plans. The complexity of the legal framework and varying levels of decentralization between sectors heightens the coordination challenge (Fig. 3.6).

In terms of water, the national government has developed a set of progressive policies and water sector-specific laws, but weak internal and external coordination makes implementation a challenge (Table 3.4). In terms of energy, the existing policies in the energy sector have been driven by the need to promote industrialization and economic development (Table 3.1). The prioritization of energy generation has often created new conflicts, for example, the expansion of coal mining in Mpumalanga, which threatens food production on high-potential land and the broader environment because of pollution. There is, therefore, a need to align energy sector policies and improve sustainability. The food sector policies have been driven by an incremental agenda, aimed at increasing production and food security (Table 3.4). However, while national food security has improved, household food security continues to grow, which highlights a lack of sustainability. Also, the expansionist approach has often come into conflict with water and environmental managers.

In addition, a review of the coherence of South Africa's WEF nexus policies and regulations found similar disconnects between the national legal framework and implementation at provincial and district levels. Local government development plans tend to see the National Development Plan (NDP) – RSA's principal development planning instrument – as a set of options to choose from rather than a framework to follow. However, local governments have significant responsibilities for natural resource management and land-use planning, and their decisions will determine whether national water, energy and food security objectives in the NDP will be achieved.

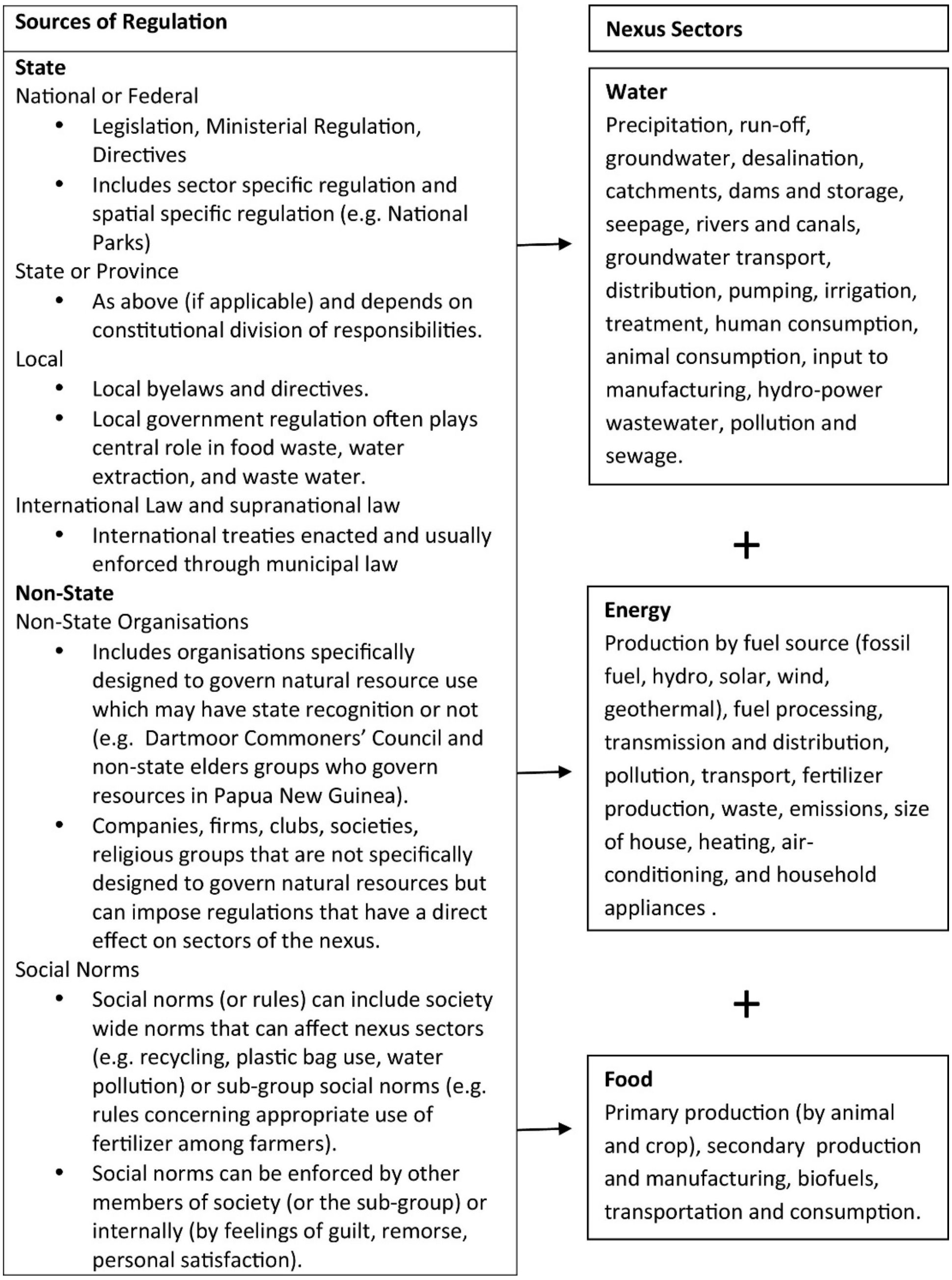


Figure 3.6 Sources of WEF regulation (Larcom and Van Gevelt, 2017).

Table 3.1 WEF nexus policy framework for South Africa

Scale	Water	Energy	Food	Environment / Climate Change / Coordination / Development
Regional / Trans-boundary	• Regional Protocol on shared Watercourses (2000) • Regional Water Policy (2005) • Regional Water Strategy (2006) • Regional CCA Strategy (2011) • Guidelines (RBOs, Protocol implementation – regional & Basins) • Joint Water Committee Treaty • Interim Inco-Maputo agreement	• SADC Protocol on Energy (1996) • Regional Energy Access Strategy and Action Plan (REASAP) (2010) • Regional Infrastructure Development Master Plan (RIDMP) and Energy Sector Plan 2012-2027 • Renewable Energy and Energy Efficiency Strategy and Action Plan (REEESAP) 2016 • Market & Investment Framework for SADC Power Projects (2016) • SAPP Power Generation and Transmission Master Pan (SAPP Pool Plan)	• Regional Agricultural Policy (RAP) (2014) • Regional Agricultural Investment Plan (2017-2022-draft) • SADC Food and Nutrition Strategy (2015-2025) (2014) • Regional Agricultural Fund	• SADC Regional Indicative Strategic Development Plan (RISDP) • The Regional Infrastructure Development Master Plan (RIDMP) (2012) • The SADC Industrialisation Strategy and Roadmap (2015-2063) • Climate Change adaptation strategy (CCAS) (2012) for the water sector – building resilience
National	• National Water Act 36 of 1998 (RSA, 1998a) • National Environmental Management Act 107 of 1998 (RSA, 1998b) • National Water Resource Strategy 2 (2012) • White Paper on a National Water Policy for South Africa (DWAF, 1997) • National Climate Change Response Policy • National Development Plan • Water for Growth and Development (DWA, 2009)	• National Energy Act 34 of 2008 • National Energy Regulation Act 40 of 2004 • National Environmental Management Act 107 of 1998 • Energy Efficiency Strategy • White Paper on the Energy Policy of South Africa (1998) • White Paper on Renewable Energy (2003) • National Climate Change Response Policy • Integrated Resource Plan (2016) • Integrated Energy Plan • National Development Plan • Department of Energy Strategic Plan 2011/12-2015/16	• Livelihoods Development Support Programme • White Paper on Agriculture 1995 • National climate change response policy • Integrated growth and development plan (IGDP) for agriculture, forestry and fisheries • Conservation of Agricultural Resources Act 1983 • Draft Preservation and Development of Agricultural Land Bill 2016	• National Development Plan (NDP) • Industrial Policy Action Plan (IPAP)

Scale	Water	Energy	Food	Environment / Climate Change / Coordination / Development
Catch-ment / Municipal	• Combined assurance model – provides assurance of key risks and controls • IUCMA Stakeholder engagement plan • Water Allocation Plan for Inkomati-Usuthu			Mbombela Municipality • Integrated Development Plan (IDP) • Municipal Reconciliation Strategy • Intergovernmental Stakeholder Engagement Strategy • Corporate Governance Framework • ISO 14001 Standards to Manage Environmental Incidents • Municipal Climate Change Strategy

3.4 STAKEHOLDER MAPPING

From the onset, the IUCMA was identified as a key stakeholder to work within this project and link the team with other relevant stakeholders through the IUCMA database. All the aspects of the stakeholders that relate to the WEF nexus and the relevance of the stakeholders to the different aspects of the WEF nexus were captured to maintain a good and robust stakeholder management system. Stakeholder engagement was done continuously to ascertain what type of information is available and the interest in and usefulness of the WEF nexus to their current operations. This greatly assisted in collecting the needed information/data and disseminating the results later in the project, as well as assisting in the project's ambition to develop a facilitative governance/decision-maker process guideline that will inform and support decision-making in the WMA.

Table 3.2 provides a summary list of stakeholders according to sector and their level of operation. The information that they are likely to be able to provide for the WEF nexus database is also listed.

Table 3.2 Summary of stakeholders in the Inkomati-Usuthu Catchment according to sector

Sector	Stakeholders	Level of operation	Information
Agriculture	DARDLR; Mpumalanga DARDLEA; NAFU ; Malelane Cane Growers Assoc.; SASRI; AGRI SA; Agri Mpumalanga; Subtrop; Transvaal Agricultural Union, etc.	Local, provincial &/or national	Production info; water, land & energy
Energy	DMR&E; DPME; PWI; Eskom; Aurecon; Coastal Fuels; Eco-Gain Consulting; LEFPA; KLCBT; SASOL; Mpumalanga Engineering; GreenCape; South African National Energy Development Institute (SANEDI);	Local, provincial &/or national	Water Use; generated energy
Environment	SAWS; ARC; SAPPI; SANParks; SANBI; WESSA; Working for Wetlands; DFFE; DARDLR; DWS; House of Traditional Leaders; Mpumalanga Wetlands Forum; Umsinsi Environmental; Earth Observation, SANSA; Mpumalanga Tourism & Parks Agency	Local, provincial &/or national	Natural resources info; water flow, use & quality info;
Industry	RCL Foods; Mondipak; Manganese Metal Company; Jab Dried Fruits; AFRIFORUM NST, etc.	Local, provincial &/or national	Energy & water use
Mining	Assmang Chrome; Barberton Mine; Vantage Goldfields; Mpumalanga Department of Mineral Resources	Local, provincial	Energy & water use
Municipal	Enhlanzeni District Municipality; City of Mbombela Local Municipality; Nkomazi Local Municipality	Local	Energy & water use
Water	DWS; WUA (Elands River; Upper Kwena, etc.); Irrigation boards (Kaap River, etc.); IUCMA; White River Valley Irrigation Board; Suidkaap Farmers Association; Sembcorp: Silulumanzi; IWR Water Resources; Dormehl Technology; Aqualytic; Enviro Eng; Zamangwane; PROXA; MIWATEK; TRAC; Waste Water Management Company, etc.	Local, provincial &/or national	Natural resources info; water flow, use & storage info;
Other government departments	Mpumalanga Office of the Premier; MDEDET; COGTA; Department of Health; National Disaster Management Centre (NDMC); DSTI; South Africa Local Government Assoc. (SALGA); DHS; House of Traditional Leaders	National & provincial	Population, Permissions, Leverage

3.5 INFORMATION GAPS

The problem of missing or limited data is common in all research and can have a significant effect on the conclusions that can be drawn from the data (Graham, 2009). Missing data presents various problems. Firstly, the absence of data reduces statistical power, which refers to the probability that the normal statistical tests will reject the null hypothesis when it is false. Secondly, the lost data can cause bias in the estimation of parameters. Thirdly, it can reduce the representativeness of the samples, and lastly it may complicate the analysis of the study. Each of these distortions may threaten the validity of the analysis and can lead to invalid conclusions. Therefore, this section on managing missing data will be expanded as the current datasets are used in the selected WEF nexus models.

Patching of climate data has been used for many years, so this experience can assist in selecting methods to use in patching missing data in the other datasets. Several different methods are used for patching and infilling climate data, namely the nearest neighbour by distance or by correlation, normal ratio, multiple regression, weighted inverse distance and/or means or weighted averages of selected stations (Bennett et al., 2007; Shabalala et al., 2019). Alternatively, interpolated surfaces can be used with various smoothing techniques or kriging to produce a gridded surface for the various parameters (Jeffrey et al., 2001). The best practice methods used for the southern African semi-arid regions will be used in this project to formulate such surfaces. Some of these methods will then be tested for the parameters from other sectors at various time and geographical scales according to the applicable information.

CHAPTER 4: SOCIO-ECONOMIC ANALYSIS

4.1 INTRODUCTION

This section's socio-economic analyses for Mpumalanga and the three district municipalities within the province draws from a thesis that formed part of the WEF nexus project within the Inkomati-Usuthu Water Management Area.

The following socio-economic aspects of Mpumalanga and its three districts were analysed: production, land use, water use, labour, income indicators, the agriculture sector and performance.

4.2 LAND USE AND PRODUCTION OF KEY COMMODITIES IN MPUMALANGA PROVINCE

The land use across Mpumalanga has been documented according to the district municipalities. It is divided into arable land, grazing land and other land uses (Table 4.1). The most important district municipality for this project is Ehlanzeni as it encompasses the Mbombela area.

Table 4.1 Land use by district municipality as of 30 September 2018 (StatsSA, 2020)

District Municipality	Total		Arable Land		Grazing Land		Other Lands	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Ehlanzeni	192 250	7.8	82 344	8.7	72 877	6.2	37 026	10.7
Gert Sibande	1 801 759	73.0	575 236	61.0	925 462	78.6	301 051	86.9
Nkangala	472 990	19.2	285 575	30.3	179 187	15.2	8 221	2.4
Mpumalanga Province	2 467 007	100	943 163	100	177 535	100	346 307	100

As at 30 September 2018, the total land used for commercial agriculture in Mpumalanga was nearly 2.5 million hectares, which represents 32.2% of the total land area of the province (7.6 million ha) (StatsSA, 2020). Commercial agricultural land in Mpumalanga comprised mainly grazing land (1.7 million ha) for livestock and game farming and arable land (0.9 million ha) for crop production.

Gert Sibande District Municipality (DM) accounts for the highest number of farms (54%) in the province, followed by Ehlanzeni (23.2%) and Nkangala (22.8%) (Fig. 4.1). This is the same for the proportion of income in the commercial agriculture industry, with Gert Sibande taking the lead (43.2%) followed by Nkangala (30.3%) and Ehlanzeni (21.5%). Ehlanzeni DM leads in the composition of employment from commercial agriculture with 51.4%, followed by Gert Sibande and Nkangala at 24.7% and 23.9%, respectively.

The commercial agriculture industry in 2017 in Mpumalanga contributed R34 396 million as gross farming income from agricultural activities. As depicted in Fig. 4.2, livestock and animal products category was the biggest contributor to gross farming income with 51.7% of the provincial total, followed by field crop products at 31.4%. Animals and animal products accounted for 65.0% of gross farming income in the Gert Sibande DM, followed by Nkangala (58%) and Ehlanzeni (12.9%). Horticultural products accounted for 58% of Ehlanzeni, followed by Gert Sibande, and Nkangala at 3.2% and 1.8%, respectively. Lastly, field crops accounted for 34.3% in Nkangala, 31.3% in Gert Sibande and 27.4% in Ehlanzeni.

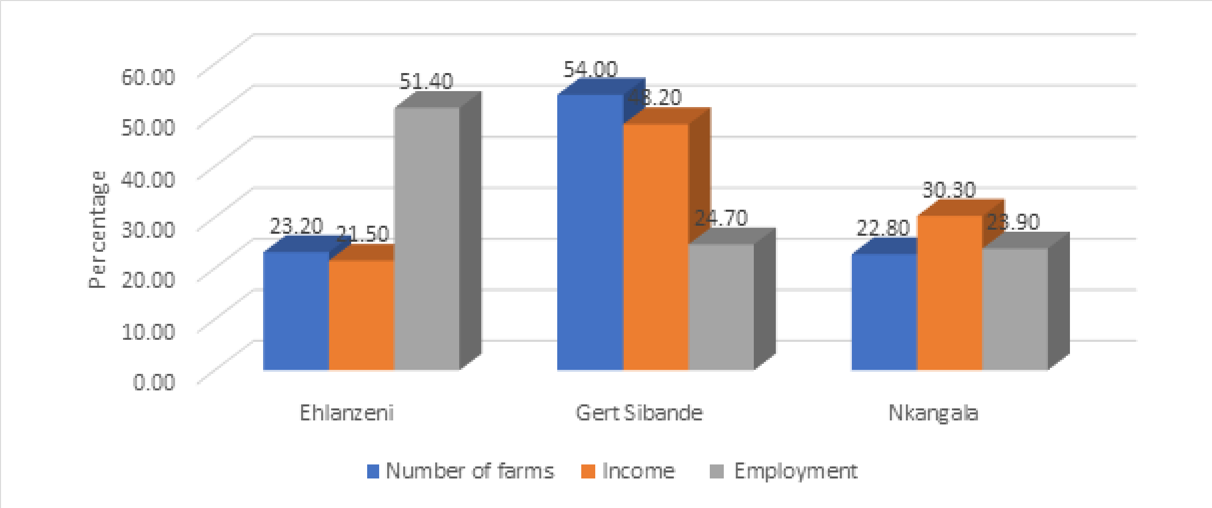


Figure 4.1 Number of farms, income and employment in the commercial agriculture industry by district municipality, as a percentage of the total, in 2017 (StatsSA, 2020).

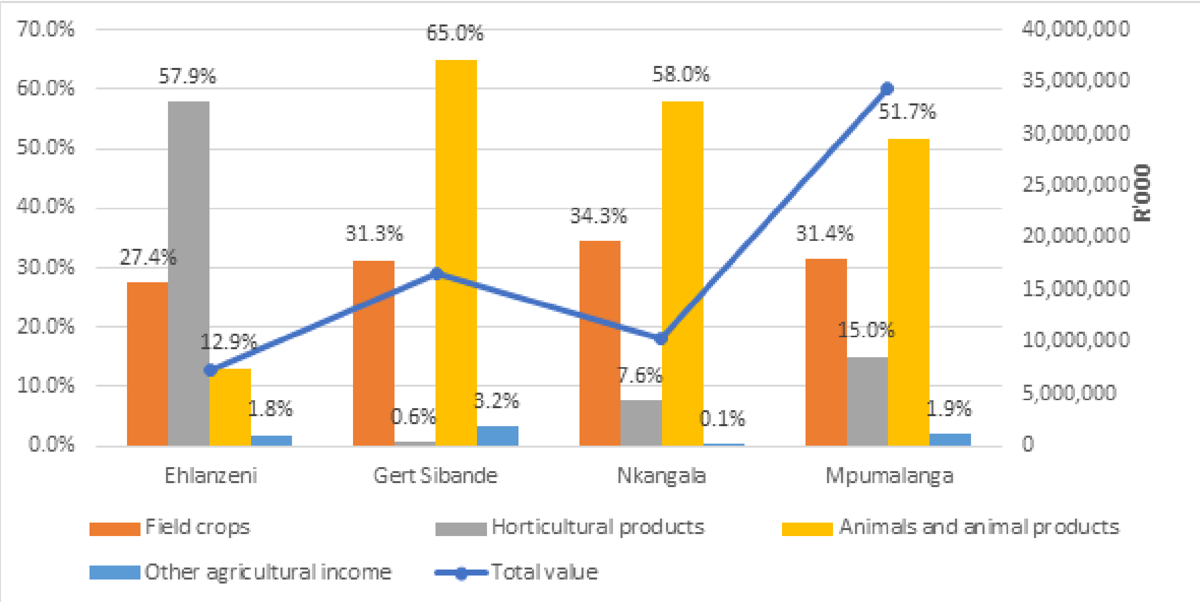


Figure 4.2 Commodity group contribution to gross farming income in the commercial agriculture industry, by district municipality, in 2017 (StatsSA, 2020).

Mpumalanga contains almost half of the country's high-potential arable land, despite being the second smallest province in South Africa (Mpumalanga Green Cluster Agency, 2021). Grazing land is used for livestock and game farming, and arable land is used for crop production. Gert Sibande DM accounted for the largest share of Mpumalanga's commercial agricultural land (73.0%), followed by Nkangala (19.2%) and Ehlanzeni (7.8%). Regarding grazing land, 93.8% was located in two districts, namely Gert Sibande (78.6%) and Nkangala (15.2%). Similarly, Gert Sibande (61.0%) and Nkangala (30.3%) accounted for over 90% of arable land (Fig. 4.3).

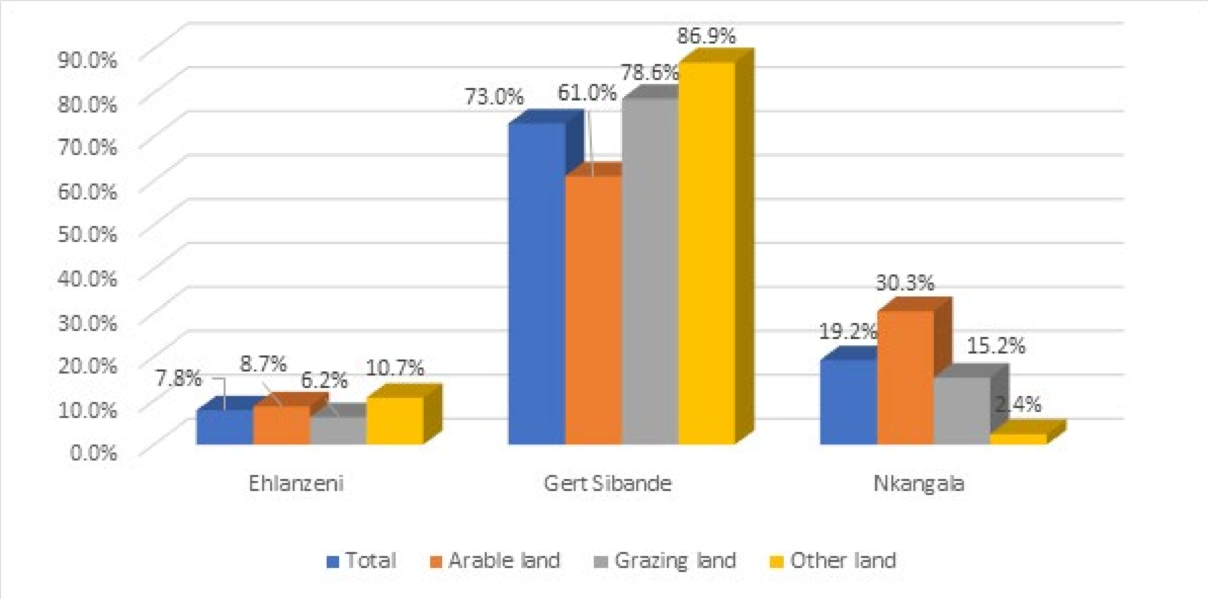


Figure 4.3 Land use by district municipality as of 30 September 2018 (StatsSA, 2020).

Field crops are important for food security and they account for the largest portion of cultivated land in South Africa. In terms of area planted, the major field crops in Mpumalanga in both 2007 and 2017 were maize and soybeans (Fig. 4.4 & 4.5). The major field crops were mostly planted under dryland, i.e. their main source of water was rain. This is expected in a water-scarce country where there are competing priorities for water use. In 2017, soybeans had the highest proportion (97.8%) of area planted under dryland. Between 2007 and 2017, maize production increased by 50.4% (from 1.6 million to 2.5 million tons) (Fig. 4.4). This was mainly driven by an increase in the production per hectare from 4.1 to 5.8 tons.

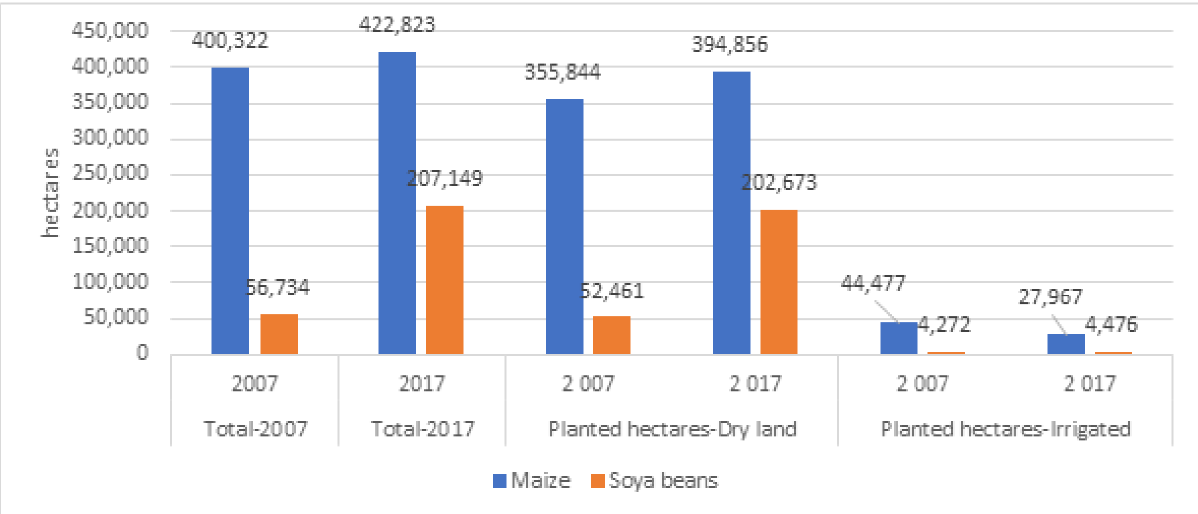


Figure 4.4 Field crops area planted in 2007 and 2017 (StatsSA, 2020).

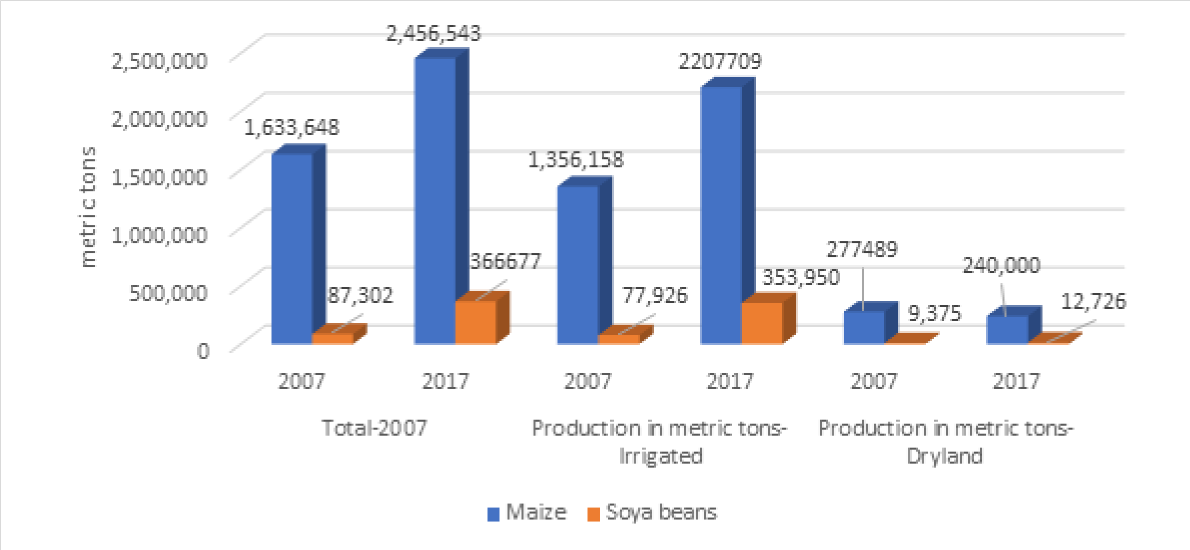


Figure 4.5 Field crops production (metric tons) in 2007 and 2017 (StatsSA, 2020).

The major vegetable crops in terms of production were potatoes, tomatoes and carrots. Although they all showed a decrease in the area planted, all three made gains in the volume of production per hectare (Fig..4.6). Regarding production, there was a decrease of 46.1% in potatoes (from 116 000 to 62 000 tons) between 2007 and 2017. Over the same period, tomatoes fell by 30.3% (from 16 000 to 11 000 tons) and carrots fell by 32.3% (from 5 000 to 3 000 tons). In 2017, the largest proportion of the province's potatoes was produced in Nkangala DM (80,9%), while Ehlanzeni produced 99.1% of the province's tomatoes and Nkangala produced all (100%) of the province's carrots in 2017. The largest proportions of all major vegetables were sold through fresh produce markets in 2017. These were the largest marketing channel for potatoes (51.3%), tomatoes (76.1%) and carrots (100%) The Gert Sibande DM produced 56.7% of maize in the province in 2017, followed by Nkangala (42.7%) and Ehlanzeni (0.7%). There was strong growth in soybeans between 2007 and 2017, namely 320% (from 87 000 to 367 000 tons), due to a large increase in the area planted. The leading districts for soybean production in 2017 were Gert Sibande (69.7% of the province's total) and Nkangala (28.9%).

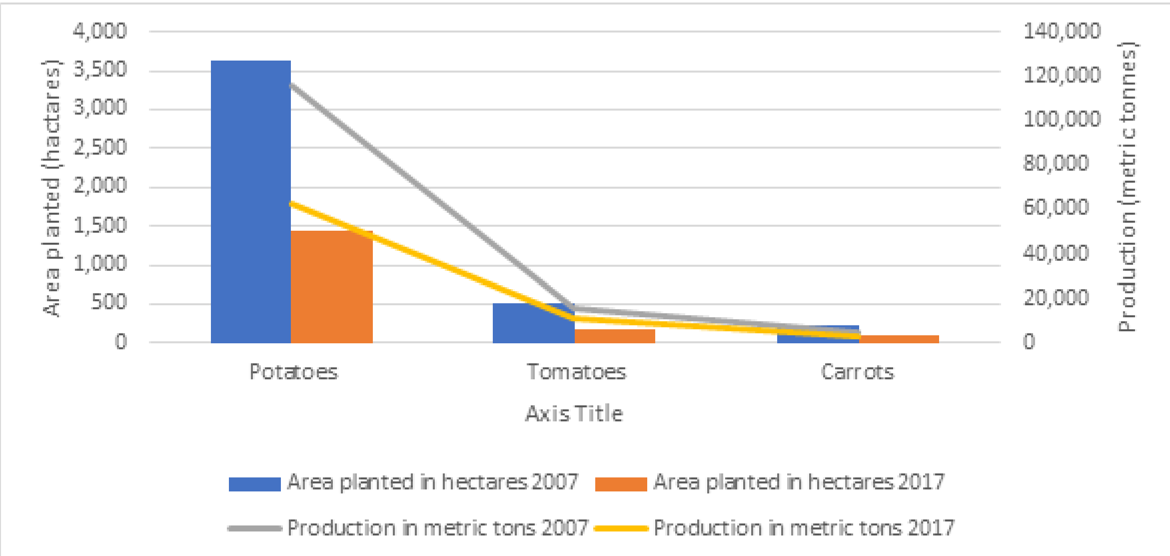


Figure 4.6 Vegetable crops area planted and production in 2007 and 2017 (StatsSA, 2020).

Citrus fruits continue to play an important role in the economy, with strong links to packaging, processing and distribution in the agricultural value chain. Oranges accounted for 4 446 ha planted in 2017, down by 58.1% from 2007 (Table 4.2). Regarding production, lemons increased by 109.7% between 2007 and 2017 (from 17 000 to 35 000 tons), naartjies increased by 35.7% (from 5 000 to 6 000 tons) and oranges decreased by 48.7% (from 312 000 to 160 000 tons). Compared with 2007, both naartjies and lemons showed a decrease in volume of production per hectare in 2017 while oranges showed an increase. The two leading districts in orange production were Ehlanzeni (78.4% of the province's total) and Nkangala (21.6%) in 2017. Lemons were also produced in Nkangala (56.0% of the province's total) and Ehlanzeni (44.0%) in 2017, while naartjies were produced only in Ehlanzeni DM (100%) in 2017. Most of the 2017 production of naartjies (81.2%), lemons (68.2%) and oranges (61.1%) were exported. The second largest marketing channel for oranges (27.0%) and lemons (16.0%) was through processing factories, while 5.2% of naartjies were sold directly to retailers, chain stores and consumers.

Table 4.2 Fruit crops area planted and production as well as livestock production in 2007 and 2017 (StatsSA, 2020)

Commodity	Area planted in hectares		Production in metric tons	
	2007	2017	2007	2017
Citrus fruits: area planted and production, 2007 and 2017				
Oranges	10 605	4 446	311 770	159 794
Lemons	418	1 035	16 503	34 606
Naartjies	159	672	4 575	6 209
Subtropical fruits: area planted and production, 2007 and 2017				
	2007	**2017**	**2007**	**2017**
Bananas	4 810	5 745	142 344	147 258
Avocados		2 922		34 150
Tree nuts: area planted and production, 2007 and 2017				
	2007	**2017**	**2007**	**2017**
Macadamia nuts	4 773	16 236	6 205	28 121
Number of animals sold and number on farms, 2007 and 2017/2018				
Type of animal	**Number sold**		**Number on farms**	
	2007	**2017**	**2007**	**2018**
Cattle	378 783	378 166	584 351	637 459
Sheep	140 541	69 563	426 619	378 571
Pigs	482 054	152 949	122 207	81 382
Chickens	222 807 665	180 969 161	32 373 948	21 972 284

The cultivation of subtropical fruits is only possible in certain parts of the country due to the nature of their climatic requirements. Between 2007 and 2017, banana production increased by 3.5% (from 142 000 to 147 000 tons) (Table 4.2). Compared with 2007, bananas showed a decrease (from 29.6% to 25.6%) in the volume of production per hectare in 2017. Bananas and avocados were produced mainly in Ehlanzeni DM in 2017. Most of the banana production (79.3%) was sold to fresh produce markets in 2017 while a significant amount of avocado production (43.2%) was exported.

There was substantial growth in the tree nut industry between 2007 and 2017. Macadamia grew by 240% in terms of area planted and by 353% in terms of nut production (production per hectare increased) (Table 4.2). Macadamia was mainly produced in the Ehlanzeni DM in 2017 and over half the nuts produced that year (53.7%) were exported.

Cattle, sheep, pigs and chickens are the most reared animals in commercial agriculture in Mpumalanga. Between 2007 and 2017, the number of cattle sold decreased by 0.2% (from 379 000 to 378 000) (Table 4.2). The leading districts in cattle sales in 2017 were Nkangala (51.8% of the province's total) and Gert Sibande (47.3%). However, the number of cattle on farms in the province increased by 9.1% (from 584 000 to 637 000) between 2007 and 2018. Compared with 2007, the number of sheep sold in 2017 decreased by 50.5% (from 141 000 to 70 000). Most sheep were sold in Gert Sibande DM (93.0%) in 2017. The number of sheep on farms fell by 11.3% (from 427 000 to 379 000) between 2007 and 2018. In 2018, Gert Sibande DM had the highest number of sheep on the farm (93.3%). There was a decrease of 68.3% (from 482 000 to 153 000) in the number of pigs sold between 2007 and 2017. Pigs were sold mainly in Nkangala DM (98.0%) in 2017. Between 2007 and 2018, the number of pigs on farms fell by 33.4% (from 122 000 to 81 000). Nkangala DM (80.8%) had the highest number of pigs on farms in 2018. The number of chickens sold decreased by 18.8% between 2007 and 2017 (from 223 million to 181 million). In 2017, the largest number of chicken sales took place in Gert Sibande (71.5%) and Nkangala (27.1%), while Gert Sibande (59.6%) and Nkangala (34.7%) reported the largest number of chickens on farms in 2018.

4.3 WATER USE, ALLOCATION AND WATER SOURCES IN MPUMALANGA PROVINCE

From the water resource systems balance shown in Table 4.3, it is clear that there are competing needs for water in Mpumalanga. The majority of the water supply systems in the province are under pressure with groundwater being considered a future water source. This is despite the numerous dams that are available in the province.

Table 4.3 Mpumalanga water resource systems balance (Balzer, 2020)

Water supply system	Major water users	System water balance	Major dams in system	Future water sources
Upper Usuthu	Chief Albert Luthuli LM; Eskom; Irrigation; Gauteng; Mkhondo	Stressed	Heyshope, Morgenstond, Westoe, Jericho	Groundwater
Upper Olifants	Eskom, Irrigation	Stressed (water quality)	eMalahleni, Loskop	Treatment of mine-affected water
Upper Vaal	Standerton, Eskom, Sasol, Secunda	Balanced	Grootdraai	-
Upper Inkomati	Chief Albert Luthuli LM, Mining, Irrigation, Eskom	Balanced	Lomati dam, Boesmanspruit, Nooightgerdact, Vygeboom	-
Lower Inkomati	Nkomazi LM, Transboundary Flow, Irrigation	Stressed	Driekoppies Dam and various smaller dams	Groundwater
Crocodile	Mbombela LM, irrigation	Stressed	Kwena and various farm dams	Crocodile East Water Project (develop dam)
Sabie	Bushbuckridge	Balanced	Inyaka, Mwarite and small dams	Groundwater

Water demand in Mpumalanga is mainly dominated by agriculture which consumes 55% of the water allocated and power generation which consumes 26% of the water allocated. The rest goes to households, other, mining and manufacturing, consuming 10%, 4%, 3% and 2%, respectively (Fig. 4.7). In a low economic growth scenario projected until 2030, water use is expected to increase by 1.6% per annum. Without extra water sources and more efficient water use (ceteris paribus), the water use deficit in Mpumalanga is expected to be 27% in 2030 compared to a 4% deficit in total water use that was experienced by the province in 2017 (DEDT, 2019).

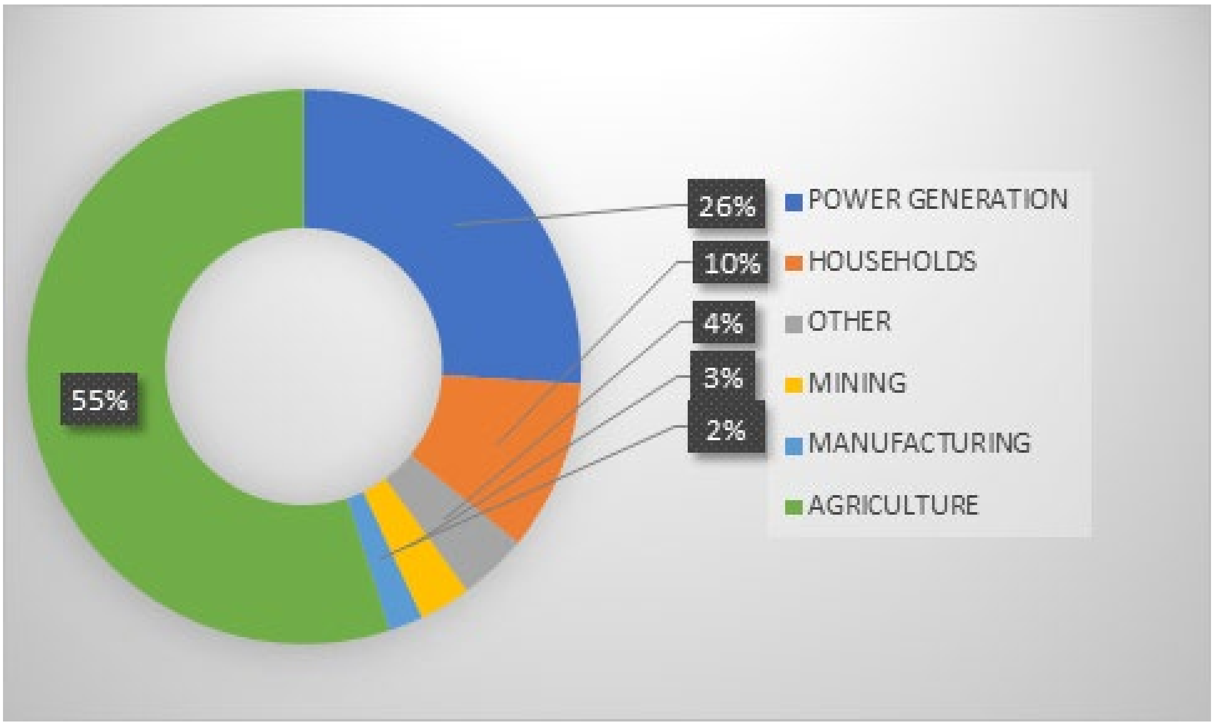


Figure 4.7 Share of water use in Mpumalanga (DEDT, 2021).

4.4 SHARE OF WATER USE IN EHLANZENI DISTRICT MUNICIPALITY

The Inkomati sub-area had a deficit of 20% in 2012 while the Usuthu sub-area had a balance of 1%, as stated by the business case for Inkomati-Usuthu Catchment Management Area. This calls for more efficient use of water and for households and municipalities to take a stand to reduce water loss and wastage, and come up with strategies for water reuse. It is clear that the majority of the water is allocated to agriculture at 76%, followed by households at 11% and hydro-power generation at 9% (Fig. 4.8). The mining and manufacturing sectors consume only at 2% and 1%, respectively.

The increase in water demand by 2030 will be mainly driven by low water tariffs, inefficient use, inadequate cost recovery, leakages, inappropriate infrastructure choices (e.g. water-borne sanitation in a water-scarce country), and increased demand in the municipal, industrial and agricultural sectors (Donnenfeld et al., 2018). The growth in demand by the municipal sector is expected to be the greatest, mainly driven by rapid urbanization, increased industrial production, commercial activity and population growth.

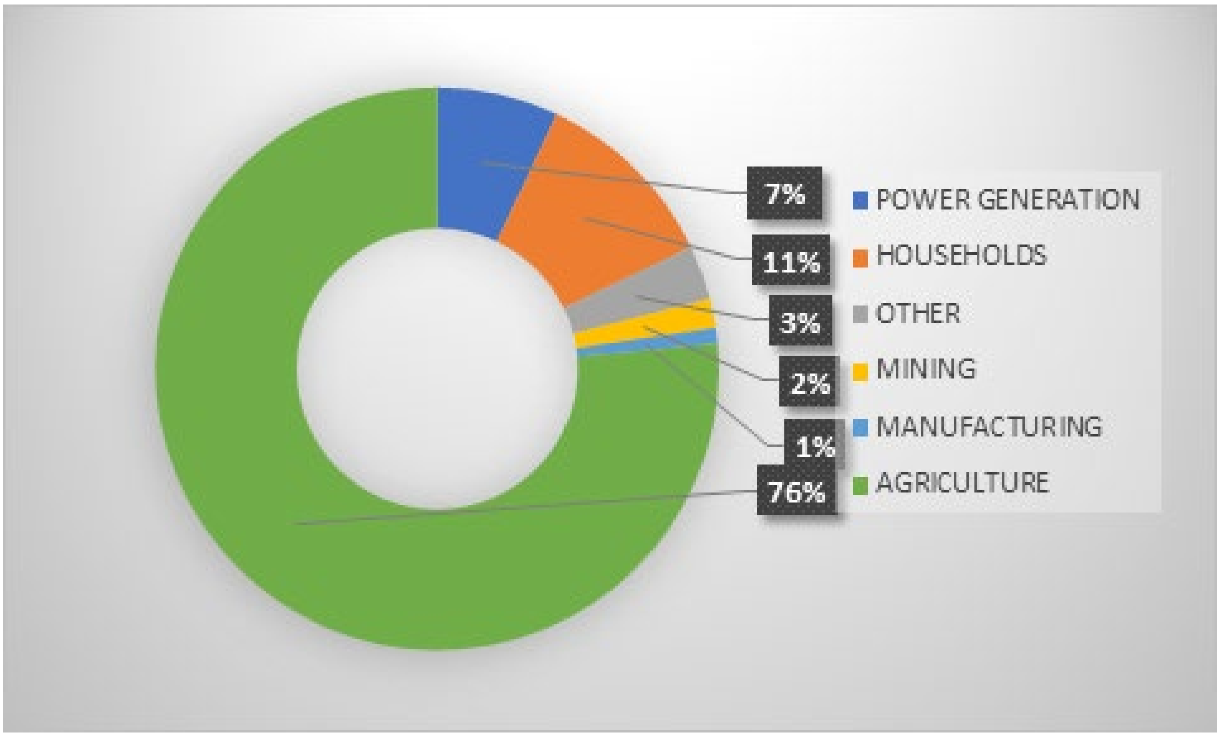


Figure 4.8 Share of water use in Ehlanzeni (DEDT, 2021).

As depicted in Fig. 4.9, Mpumalanga has a low proportion of households that regard the quality of water as safe to drink. However, this province had a high proportion of access to safe drinking in 2002 at 94% which declined significantly to 87% in 2006. As such, Mpumalanga is one of the provinces that reported declines in the proportion of households that regard the quality of water as safe to drink between 2002 and 2017. This shows that the province needs to improve its access to quality water.

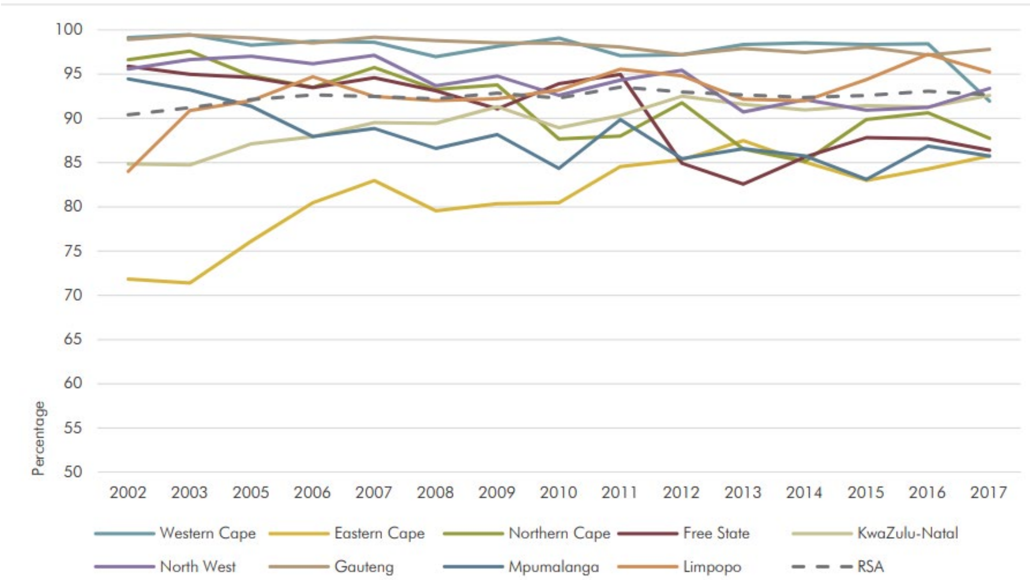


Figure 4.9 Proportion of households that regard the quality of water safe to drink by province (2002-2017) (StatsSA, 2019).

4.5 INCOME AND EQUALITY DISTRIBUTION IN SOUTH AFRICA

South Africa has the highest imbalanced income distribution in the world (DEDT, 2021). The Gini-coefficient for South Africa is higher than that of Mpumalanga and its three district municipalities (Table 4.4). The Gini coefficient ranges from 0 (perfect equality, where all households earn the same income) to 1 (perfect unequal society). In 2018, all three district municipalities registered inequality of 0.60% which is higher than in 1996. This is not good for the country as you are not expecting a regression in terms of economic indicators, which is equality in this case.

Table 4.4 Gini-coefficient (1996-2018) (HIS Markit-Rex, October 2019)

Region	1996	1999	2004	2009	2014	2018
South Africa	0.61%	0.65%	0.65%	0.64%	0.63%	0.63%
Mpumalanga	**0.59%**	**0.63%**	**0.64%**	**0.62%**	**0.61%**	**0.60%**
Gert Sibande	0.59%	0.64%	0.64%	0.62%	0.61%	0.60%
Nkangala	0.58%	0.62%	0.63%	0.61%	0.60%	0.60%
Ehlanzeni	0.58%	0.63%	0.63%	0.61%	0.60%	0.60%

In future (ceteris paribus), it is projected that the inequality coefficient for Ehlanzeni DM will decline at a slower rate (Fig. 4.10). This is good for the province, especially, when there are efforts of removing discriminatory policies for equal distribution of resources, promoting shared prosperity and obtaining fair benefits from economic activities in South Africa. These efforts implemented by the government will help to promote social capital and stimulate the economy to improve welfare by reducing inequality.

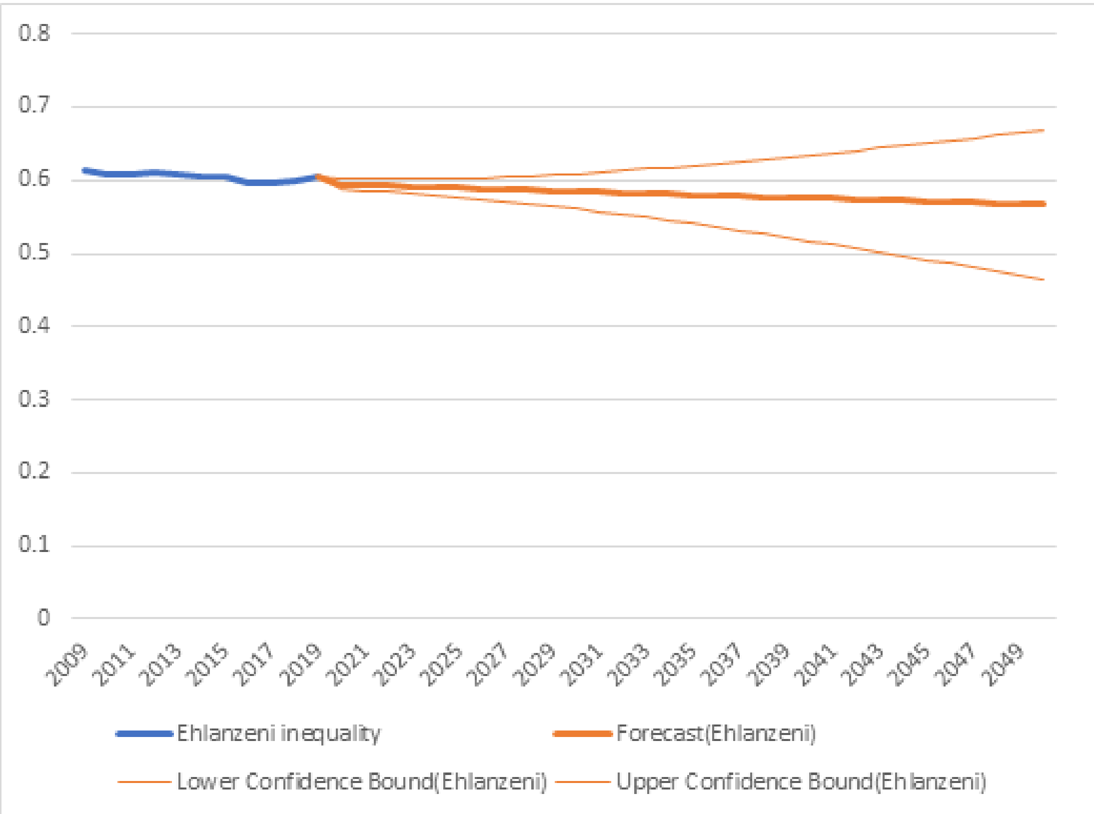


Figure 4.10 Inequality coefficient for Ehlanzeni and future projections.

According to DEDT (2020), the National Development Plan (NDP) targets 40% of households in South Africa to at least earn 10% of total income by 2030. As stipulated in Table 4.5, 40% of the households in Mpumalanga in 2018 earned 7.8% of the total income. This is a regression when compared to the 9% of the total income earned in 1996. Actually, it is evident that South Africa and all the districts in Mpumalanga have regressed over the years in achieving this objective.

Table 4.5 Share of income earned by the poorest 40% (1996-2018) (HIS Markit-Rex, October 2019)

Region	1996	1999	2004	2009	2014	2018
South Africa	7.7%	6.1%	6.2%	6.6%	6.8%	6.7%
Mpumalanga	9%	7.3%	7.0%	7.6%	7.8%	7.8%
Gert Sibande	8.8%	7.1%	6.7%	7.3%	7.5%	7.8%
Nkangala	8.5%	7.1%	7.0%	7.4%	7.5%	7.6%
Ehlanzeni	9.6%	7.7%	7.4%	8.2%	8.4%	8.4%

4.6 POVERTY AND UNEMPLOYMENT IN MPUMALANGA

Mpumalanga has experienced an increase in both the provincial unemployment rate and poverty rate since 2015, in line with the weak economic environment and low provincial economic growth rate. The province's unemployment rate was highest in 2021, at 36.6% (Fig. 4.11). Recently, the country has seen an increase in the youth (15-34 years) unemployment rate and Mpumalanga is not spared from this. The poverty rate in Mpumalanga also worsened from 63.2% in 2013 to 50.8% in 2020 (Fig. 4.12). In 2010, Mpumalanga observed the highest level of poverty, recording 72.8%. It is projected that both the unemployment rate and the poverty rate are expected to increase consistently by 2050.

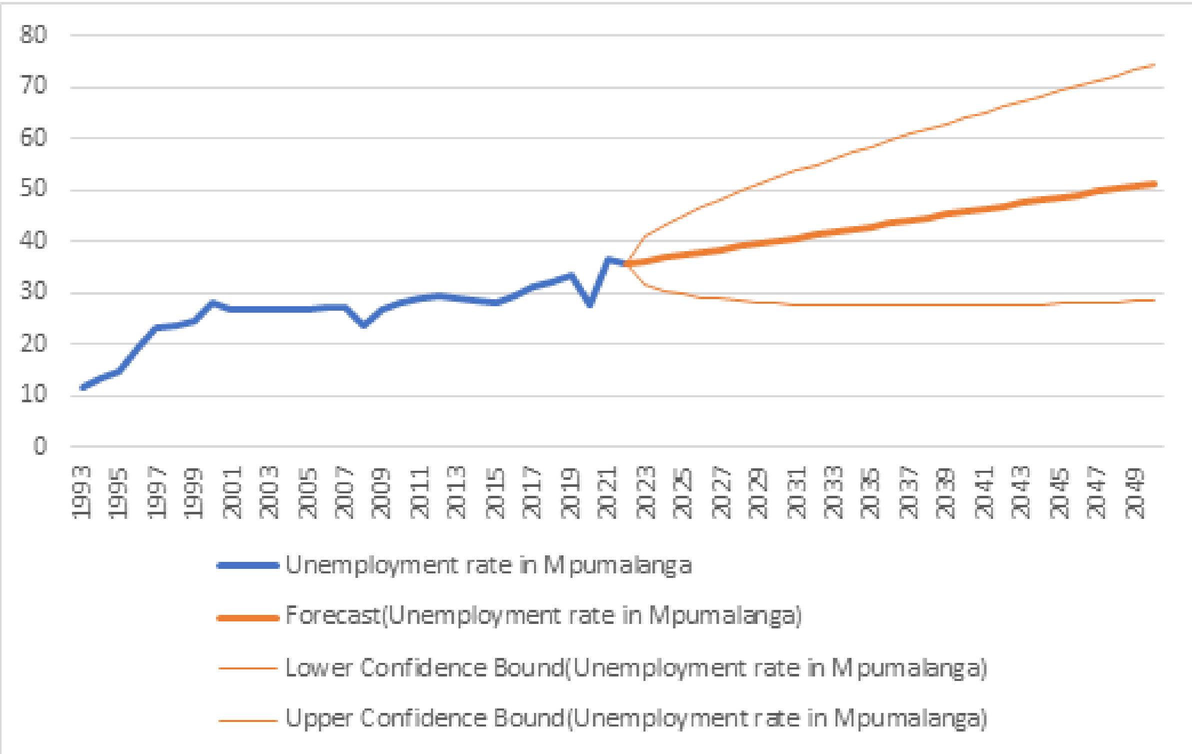


Figure 4.11 Unemployment rate in Mpumalanga (World Bank data, 2023).

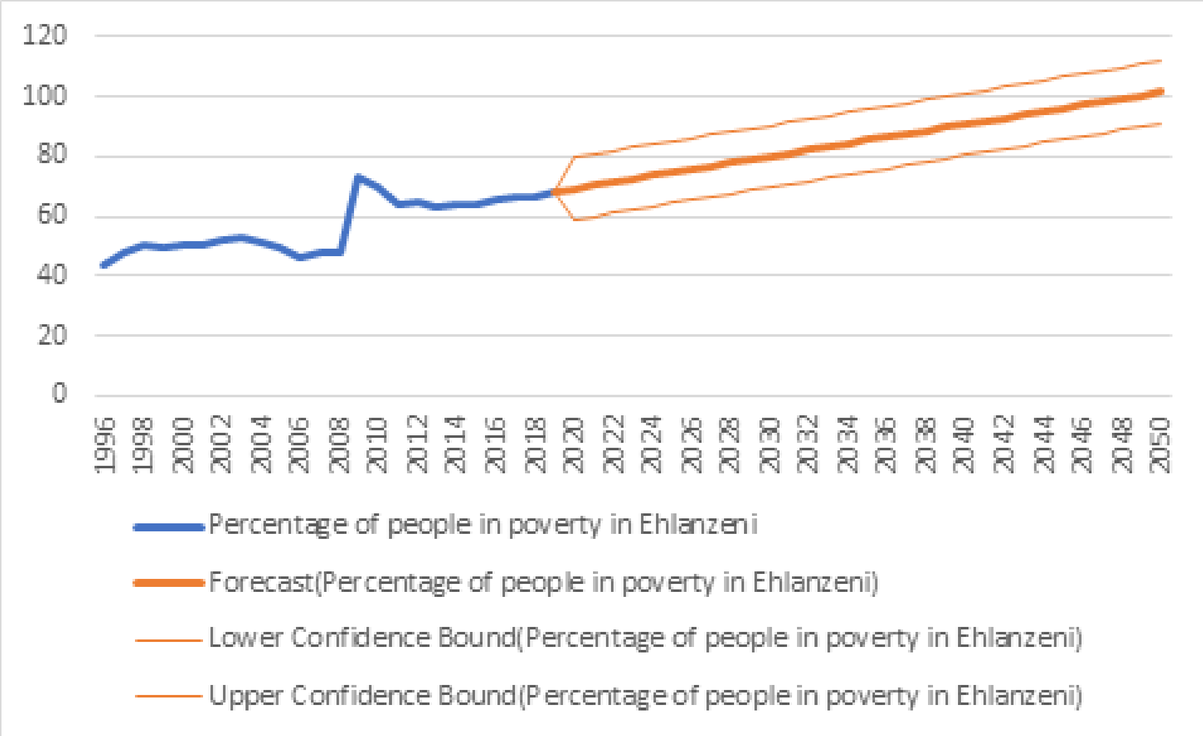


Figure 4.12 Poverty trends in Mpumalanga (World Bank data, 2023).

It is interesting that the forecast for poverty level has narrower expected variation than the predicted level of unemployment. This is despite the higher variation in poverty level in the past, particularly influenced by global shocks such as the 2008 financial crisis.

CHAPTER 5: METHODOLOGY

5.1 INTRODUCTION

This chapter unpacks the methodologies that were used in gathering data from different sources for the various aspects of the project. As this project has a mixed method research design, it includes both quantitative and qualitative data collection methods such as semi-structured interviews, focus group discussions, participatory scenario development, as well as the application of the WEF nexus model. These methods were chosen in order to triangulate the results. The WEF nexus tools were investigated then, after collecting the input data, they were applied to the Crocodile River Catchment at several temporal and special scales. The stakeholder engagements included awareness presentations as well as dedicated participatory data collection activities. The semi-structured interviews and questionnaires provided scoping information for the broader WEF nexus stakeholder group in the case study area. This was followed up with a participatory scenario development process to understand how stakeholders collectively engage on future development scenarios related to the WEF nexus. Lastly, the team conducted a validation workshop for the validation and re-design of the future scenarios that were developed by stakeholders during the participatory workshop.

5.2 STAKEHOLDER ENGAGEMENTS

The research team introduced the project to stakeholders and existing forums/networks/associations. The platforms included inter alia the Mpumalanga provincial government, Research and Development Committee, Crocodile River Catchment and Lower Komati Management Forums (on more than one occasion), Inkomati-Usuthu Catchment Management Agency, Mbombela Local Municipality and the Mpumalanga Provincial Climate Change Forum.

Primary data was collected through semi-structured interviews, focus group discussions, questionnaires and consultative discussions with leading stakeholders of the IUCMA and across the different relevant sectors (policy-makers; officials from the Department of Water and Sanitation, Department of Energy, Department of Agriculture, Land Reform and Rural Development and local municipalities; tribal authorities, irrigation boards / water user associations, etc.). Purposeful sampling and the snowballing technique was used to recruit Water User Association and Catchment Management Forum representatives, and government officials at multiple levels (local/district municipality, provincial and national) for interviews. Together with decision-makers practising in the WEF nexus domain, a facilitative methodology was developed and applied to trace a theory of change pathway that can be followed to implement and optimize WEF related decisions.

Focus group discussions (FGDs) were conducted with stakeholders from the IUCMA and Mbombela LM along with stakeholder validation workshops to gather information about existing data and information systems in the study area that will be used to feed into the analytical framework. The FGDs for each of the two stakeholder groups deep-dived into the themes that emerged during the participatory scenario development. The main themes were labelled and discussed according to sub-themes, which have also emerged from the FGDs. One FGD involved a management group of eight IUCMA individuals around the various decision structures involved in the distribution and/or development of water, energy and food nexus policies. Participants included high-level senior staff from the hydrology unit and staff from the institution and participation division. The second FGD was held with officials from Mbombela LM, from the Environmental Management and Planning Department.

5.3 DATA PROCESSING METHOD FOR FOCUS GROUP DISCUSSION INFORMATION

The FGDs conducted were transcribed and the transcripts were sanitized by removing all identity markers linking the text to specific participants, to ensure confidentiality. Based on the FGDs conducted, two stakeholder groups were formed and used to group the transcripts, namely municipal officials and CMA staff members. Transcripts categorized under these stakeholder groups were merged into a single document per group in Word format. A macro was then created and enabled to allow for inductive and emergent thematic coding (ETC) (also referred to as ‘open coding’ by grounded theorists or ‘latent coding' (Shapiro and Markoff, 1997) using comment boxes. ETC is a qualitative data analysis approach in which the text (in this case FGD transcripts) is read several times to identify themes that emerge from the data (Amundsen and Sohbat, 2008).

An independent coder then coded all transcripts into themes, coding anything that might be relevant from as many different perspectives as possible. Codes could refer to substantive things (e.g. particular behaviours, incidents or structures), values (e.g. those that inform or underpin certain statements, such as a belief in the link between drought and punishment by the ancestors), emotions (e.g. sorrow, frustration, hopelessness) and more impressionistic or methodological elements (e.g. respondent found something difficult to explain, interviewee became emotional, interviewer felt uncomfortable) (Gale et al., 2013; Saldaña, 2009). Themes were identified through inductive reasoning using two major methods of theme identification: repetition – phrases or opinions that were consistently mentioned and indigenous categorization – identifying phrases or words specific to the situation or sub-culture (Pattinson et al., 2017; Ryan and Bernard, 2003). Higher order themes were identified using both methods whereas lower order themes were low in repetition, thus less descriptive of the wider stakeholder group community. This was then transposed into Excel to allow for easy extrapolation across stakeholder groups and themes.

The process was documented to capture decision-makers' interactions with key stakeholders, critical negotiations, and required trade-offs and decision points. Ultimately, this means developing and piloting a facilitative decision-making process that guides decision-makers on how to understand options analysis, assess trade-offs, and make development decisions using the analytical tool. This process is written as a user-friendly process guideline document that could guide decision-making in other catchments (see separate "Facilitative Guideline for Policy-makers"). The guideline is documented in such a way that it is aligned to the selected WEF nexus tool.

5.4 WEF NEXUS MODELS / TOOLS / FRAMEWORKS

A literature search was made for all scientific articles related to WEF nexus tools and/or frameworks. A comprehensive list was formulated and divided into categories according to the sectors and aspects addressed. They were also reviewed according to availability and ease of application at the catchment scale required for this project. Then a shortlist was made of possible tools to be used for the Crocodile River Catchment calculations.

A detailed compilation of the type and form of data needed to utilize the WEF nexus tools was made. All possible sources of such data for the South African situation were compiled together with a list of interested stakeholders. Data was then collected for the Mpumalanga Province and specifically for the Crocodile River Catchment and the Mbombela LM.

Calculations were made using the WEF nexus indices used in the Analytical Livelihoods Framework (ALF) for each of the sectors, namely water, energy and food. Calculations were made at Mpumalanga provincial level and also at Mbombela municipal level. This was done as it was too difficult to obtain data at the catchment level as the Crocodile River stretches across several provinces and municipalities which are the usual reporting levels or categories.

Agriculture is the highest user of water in this water-scarce area that will only become more water stressed in future. Therefore, calculations were made using WEF indicators and LCA to compare water use and efficiency of two crops, namely sugarcane (dominant in lower reaches of the Crocodile River Catchment) and macadamia nuts (more recently introduced in the catchment).

Water allocation in the Crocodile River Catchment is a task of IUCMA and due to the increasing demand for water from the municipal sector, alternative sources or storage need to be addressed in the near future. Therefore, a comparison of plausible scenarios or alternatives to address the projected water shortages was made using the WEF nexus approach. The two future scenarios addressed are the building of a new dam and the changing to other crops that use less water. The results from these WEF indicator calculations can then be used to inform decision-makers.

WEF nexus tools have been used as an indicator in South Africa by a variety of researchers (Lawford, 2019; Mabhaudhi et al., 2019a&b; Mabhaudhi et al., 2021; Nhamo et al., 2018, 2020a&b; Nhamo and Ndlela, 2021; Simpson and Berchner, 2017). These indicators are site/location-based and are usually based on system conditions. The ALF is an analytical framework used in this project as part of the quantitative component. It was developed by defining indicators for three resource components with societal impact, namely water, energy and food. This tool assists in integrating the effects of these three resource interactions within the chosen catchment (Mabhaudhi et al., 2019b), and then indicators are calculated into a composite score (Nhamo et al., 2020a) (Table 5.1).

Table 5.1 WEF sector resources and sustainability indicators with units as described by Nhamo et al. (2020a) for WEF nexus interactions

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

The WEF nexus tool allows the user to select indicators that will respond to different scenarios such as a population with varying food self-sufficiencies together with a range of water and energy availability levels, and with links to various countries according to the export destinations of the base crops. The output can also be a summary of other information such as:

- Water requirements (m^3)
- Local energy requirements (kJ)
- Local carbon emissions (ton CO_2)
- Land requirements (ha)
- Energy consumption through import (kJ)
- Carbon emissions through import (ton CO_2).

The results for these indicators are presented in the form of a spider diagram to reveal the relative strengths and weaknesses in each sector, and to give guidance about priority areas where interventions are needed to bring balance and cohesion across the sectors. From this framework, the user can evaluate synergies and trade-offs in resource planning and utilization. The ALF model established quantitative relationships across the WEF sectors, simplifying the interlinkages among resources, by using relative indicators for the area or location analysed. It has been applied at a national level for South Africa as a case study, but could be adapted for other scales and periods as defined by the user (Nhamo et al., 2020b). It has also been used to link the WEF sectors to the Sustainable Development Goals (SDGs) and their associated indices. It can then be an enabler to promote socio-ecological sustainability across the three mentioned sectors. WEF nexus planning can contribute towards informing strategies for sustainable and inclusive socio-economic development, safeguarding resource securities (water, energy and food) and helping to improve the livelihoods of vulnerable communities.

Catchment and sub-catchment linkages to the WEF demands are mostly competitions for the limited water by various industries. In crop production, this means covering the wide range of different environmental impacts and including all the various activities involved, ranging from fertilizer production, growth season activities up to the processing of by-products after harvest and waste. Other impacts especially in agriculture are caused by irrigation and drainage in catchments. The range of assessments is dependent on the user of the framework.

5.4.1 Tools to calculate WEF nexus components at provincial, catchment and district municipality level

Various WEF nexus framework tools have been developed at different levels, internationally and nationally (Daher and Mohter, 2015). Other framework tools will also be applied, compared and tested for relevance to decision-making, and these include the use of Sustainable Performance Indicators (SPIs) by Zarei et al. (2021). The procedures used will include a quantitative process to calculate a range of indices for each of the component sectors that can be used to assess WEF nexus trade-offs. The integration of the various tools may lead to the development of an applicable WEF nexus framework tool for specific use at provincial and municipal levels. Fernández-Ríos et al. (2021) used the WEF nexus approach to profile food security, using WEF nexus indicators, a WEF nexus tool and SDG indices as tools. Srigiri and Dombrowsky (2021) mentioned that the use of WEF is important in guiding and understanding the interdependencies with the sectoral SDGs, particularly goals 2, 6 and 7 (Srigiri and Dombrowsky, 2021). When considering the SDGs and links to WEF, Mabhaudhi et al. (2021) used the ALF as one of the tools that are used in WEF nexus analysis as it can be assessed through measurable indicators.

The sectoral information has been identified from various sources. For water one needs information on sources; availability, needs, consumption and withdrawal requirements. In terms of food, information on local food production versus imported (e.g. sugarcane), food processing (e.g. sugar mill), as well as other crop production activities is needed. For energy, the information needed is to identify sources of energy used by the water sector, energy for agricultural production, and energy used in other sectors such as municipalities. The applicable data selection can be at a daily, monthly and/or annual time scale. The indicators can be used to interpret data and create different scenarios with varying water-energy-food self-sufficiencies. This assists in decision-making concerning land requirements (ha), selected crop yields (ton), energy requirements (kJ), energy consumption through import (kJ), type of energy to suit a selected scenario, import and export management by government and other decision-making stakeholders such as the municipalities. The results can be related to policy and regulation of export and import of agricultural products and energy regulators such as Eskom.

5.4.1.1 Analytical Livelihoods Framework (ALF)

The ALF is an analytical tool that was developed by firstly defining indicators for each of the components – water, energy and food – and then calculating the indicators into a composite score (Nhamo et al., 2020a). The water indicators describe the availability of water as the proportion of available freshwater resources per capita (m^3/capita) compared with the water productivity as the value of crops produced per unit of water used ($/$m^3$). For the energy part, the indices are calculated from the proportion of the population with access to electricity compared to the productivity calculated from the energy intensity in terms of primary energy produced and GDP (MJ/GDP). For the food section of the calculation, one uses an indicator of self-sufficiency from the prevalence of moderate or severe food insecurity in the population (%) compared to the cereal productivity as sustainable agricultural production per unit land area (kg/ha). However, the cereal productivity index is clearly not applicable for this catchment and caloric/nutritional values of the selected crops were used instead. These indicators are then presented in the form of a spider diagram to reveal the relative strengths and weaknesses which can give guidance about priority areas where interventions are needed to bring balance and cohesion across the sectors. As water and food together with an energy supply are vital to human livelihoods, the integration of these "access" and "availability" indicators is relevant to the livelihood status in the area. This type of analytical framework enables one to evaluate synergies and trade-offs in resource planning and utilization, in a way that other WEF tools has not achieved. However, this needs to be further developed to allow for input on governance issues particularly on cross-sectoral policy coordination (Rasul and Neupane, 2021), as missing links to policy-making, decision-making, lack of synergies and trade-offs have already been identified. So, the ALF model has established quantitative relationships across the WEF sectors, thus simplifying the intricate interlinkages among resources, by using relative indicators. It has previously been applied at a national level for South Africa on an annual basis as a case study (Nhamo et al., 2020b), but needs to be adapted for other scales and periods by developing suitable indicators at a smaller spatial local scale such as in this project.

The ALF includes indicators for each of the three sectors, namely water, energy and food, that are important aspects of the current project. However, some alternative methods and additional indices were included to address catchment specific aspects and broaden the reach of this approach with calculations at catchment and provincial scales. Given the many temporal and spatial scales of WEF nexus decisions, it would be helpful to have regional data frameworks to facilitate the transfer of data and improve its utility for use at local scale (Lawford, 2019). Although the ALF covers the physical aspects of the WEF nexus in a logical fashion, several missing links have been identified. These include aspects of policy-making, decision-making, lack of synergies and trade-offs that are not included into the indices described (Simpson and Berchner, 2017). Therefore, as these are important aspects of the current project, some alternative methods or means or additional indices need to be included to address these aspects and broaden the reach of the WEF nexus approach and calculations to be used at catchment scale. This can also assist in making the WEF nexus methodology more useful to decision-makers.

5.4.1.2 Life Cycle Assessment (LCA)

The LCA framework can be used to determine areas or activities of impact and compare reduction strategies for production systems. LCA methodology was originally developed for industrial operations but has been expanded to a wider range of fields, including agriculture. The LCA provides a methodology to investigate environmental impacts from a holistic perspective. However, limited applications of LCA have been done in the South African agricultural sector. Other LCA advantages include the improvement of system efficiencies leading to decreases in environmental burdens (Pryor et al., 2017). Van der Laan et al. (2015) used LCA to quantify the potential environmental benefits of using improved water and nitrogen fertilizer management practices by sugarcane farmers. There are numerous factors that increase the complexity of determining impacts associated with agricultural production, including multiple products from a single system, regional- and crop-specific management techniques, temporal variations (seasonally and annually), together with spatial or dimensional aspects. In this project it could be an assessment of sub-catchment linkages between the WEF components with changing demands, as food and energy sectors (including urban aspects) are in competition for water due to use by various groups at sub-catchment level. For crop production, this means covering the wide range of different environmental impacts and including all activities involved, ranging from fertilizer production, growth season activities right through to the processing of by-products after harvest and management of waste. Other interactions in agriculture include aspects of irrigation demand and drainage in such catchments. The LCA is divided into four distinct components: (1) scoping and goal setting; (2) compiling quantitative data on direct and indirect materials/energy inputs and waste emissions; (3) impact assessment; and (4) improvement assessment (El-Haggar, 2005).

The range of assessments that would be included is dependent on the specific questions that a user of the framework wants to evaluate. Therefore, it is possible to use the LCA to evaluate the end-to-end use of water and energy for the sugar and/or macadamia sectors, and include aspects of policy formulation and decision-making, while attempting to address synergies and trade-offs between the sectors. This project will use LCA to compare sugarcane and macadamia nuts as important agricultural products featuring in the catchment, as well as other alternative crops grown along the Crocodile River. The impact on water production and energy generation will be assessed. This can also be achieved through the assessment of biophysical indicators, such as water use efficiency of the crops. The outputs could help inform water allocations for the agricultural industry. This will assist the IUCMA and other agricultural stakeholders in policy and decision-making. In addition, a database of assessments on the various crops in the catchment could be established.

5.4.1.3 Sustainability Performance Indicators

As the two previous methods have not been conducted at catchment level, an alternative method was sourced to estimate more site-specific metrics. The study by Zarei et al. (2021) in a catchment in Iran investigated the integrated assessment of agricultural sustainability from the perspective of water, energy, food and associated environmental impacts. As in other situations, sustainable development depends on the sustainability of water resources and the link between society and environment. Their study, therefore, calculated the effect of WEF components using Sustainability Performance Indicators (SPIs) to assess the sustainability of the agricultural activities in the region. These SPIs can then be used in an integrated assessment and for decision-making based on WEF nexus thinking to support optimal resource management while taking the wide range of economic, social and environmental components into consideration. Zarei et al. (2021) used several SPIs for each of the WEF components but in this study an equal number of indicators will be used for each of the factors. Zarei et al. (2021) selected 17 possible SPIs to assess the WEF nexus in that agricultural system. The calculation of the six selected SPIs in this project follows the methods used by Zarei et al. (2021). The selected SPIs for each sector are directly linked to SDGs for the results to be interpreted within the South African development strategies (Table 5.2). These relationships and the detailed methods used to calculate them will be discussed in more detail later together with the results.

Sustainable development depends on the sustainability of water resources and the link between society and the environment. The calculation of the effect of WEF components using SPIs to assess the sustainability of agricultural activities is critical. These SPIs can then be used in an integrated assessment and for decision-making based on WEF nexus thinking to support optimal resource management while taking the wide range of economic, social and environmental components into consideration.

Table 5.2 SPI indicators used by Zarei et al. (2021)

Sector	Index	SDG
Water	Water stress	#6
	River flow index for dry season	#14
	Reliable water supply	#6
	Groundwater level sustainability	#15
	Irrigation performance index	#2
	Water consumption per kg of product	#2
	Available water index	#6
	Water efficiency index	#2
	Water economic efficiency index	#8
	Water resources vulnerability index	#10
Energy	Energy performance index	#7
	Energy sustainability index	#7
	GHG emissions from energy use	#13
Food	Food security index	#2
	Revenue index	#8
	Price index	#12
	Farm net value added	#2

The calculation of indices was as follows as suggested by Zarei et al. (2021):

Water Stress for a specific period:

$$Water\ Stess\ Index = \frac{Supply}{Demand}$$

Water Efficiency:

$$Water\ Efficiency\ \ Index = \frac{Crop\ Water\ Requirement}{(Water\ from\ Irrigation + Rainfall)}$$

Calculated Land:

$$Cultivated\ Land\ Index = \frac{Cultivated\ Land}{Total\ Land\ Cover}$$

These parameters were calculated for the Mpumalanga area focussing on the Crocodile River Catchment and Mbombela Local Municipality areas.

5.5 SCIENCE COMMUNICATION

5.5.1 Design and methods

The sample population was involved in this developmental programme through a process of empowerment known as participatory communication – engaging beneficiaries to identify the group's issues, providing the resources, knowledge, or skills needed to solve the problem, and allowing them to regain power over their life (Figueroa et al., 2003).

Mixed design methods were also used in this part of the study. Through the use of different methods, qualitative, analytical, and theoretical research approaches, one is able to reach insightful conclusions and expand the understanding of the situation. The mixed-method approach allows one to benefit from both qualitative and quantitative designs to describe, analyse and interpret the data. The qualitative approach worked well for learning specifics about the beliefs, attitudes, actions and social settings of the research region.

The use of open-ended questions allows participants to react in their own words rather than requiring them to select from predetermined responses as is the case with quantitative approaches. This flexibility of qualitative research methodologies enables one to freely investigate participant replies, so that data collection and data analysis take place simultaneously (Ary et al., 1990). The data analysis process is inductive, enabling organizing data into manageable bits, synthesizing it, looking for patterns, determining what is significant and what can be learned, and selecting what to share with others.

5.5.2 Sampling method

The population was made up of members of the WRC WEF nexus project team, the Crocodile and Sabie-Sand Catchment Management Forums, provincial and local government employees from the three sectors, emerging farmers and school children. It is important to build relationships with all stakeholders as the success of the research lies largely in their cooperation with the researcher. Where necessary, contact was done through e-mails, phone calls, meetings and group contact sessions. In qualitative research, only a sample of a population is purposively selected (Mack et al., 2005). A sample size of 50 participants was selected (Table 5.3), so 50 questionnaires were sent out with 12 returned to date.

Table 5.3 Population of those completing the survey spread over the various sectors

Sector	No. of stakeholders / Participants
National Departments	3
Provincial Departments	6
Municipalities (District and Local)	10
Agriculture	15
Water User Associations	6
Industry	2
Energy	2
Conservation/ Environment	3
Mining	3
Total population sample	**50**

5.5.3 Data types and sources

The data used was mostly the Reference Group meeting minutes and institutional reports of various stakeholders, especially those relating to stakeholder participation and the interconnectedness of the WEF nexus approach. Such documents were the draft Catchment Management Strategy, IUCMA stakeholder participation framework, communication strategy, National Intergovernmental framework, Department of Agriculture communication strategy, and Crocodile River Catchment Management Forum to mention but a few. The documents were interrogated to verify the inclusion of programmes and activities geared towards stakeholders and public communication activities, and the acknowledgement of other stakeholders and their roles within the WEF nexus. Other important aspects were stakeholder empowerment initiatives, collaboration and involvement.

5.5.4 Science communication questionnaire

Questions were formulated to collect data on the understanding of participants about the WEF nexus project. The questionnaire was answered on an anonymous basis to allow for maximum participation and free expression of ideas without fear or prejudice. The questionnaire was administered by ensuring that each participant was comfortable and free to participate. Participants' language was considered to ensure they all were given the freedom to express themselves. Where possible, interpretation was provided at the request of a participant, although this is not desirable because interview responses are supposed to be anonymous and private. The questionnaire was administered to all participants, including the administrators of the three aspects of the WEF nexus, which are water management institutions, the Department of Agriculture, and the Department of Energy at a local level. The intention was to test if the findings from administrators and ordinary stakeholders differ, and it is desirable to incorporate them into their decision-making processes.

CHAPTER 6: USE AND APPLICATION OF WEF NEXUS TOOLS

6.1 INTRODUCTION

The agricultural sector is crucial to socio-economic development through the production of food and employment contributing vastly to economic security, stability and sufficiency in a developing country such as South Africa. However, the future and sustainability of this sector depend on critical issues such as climate change, resource management, population growth, urbanization, skills shortages, changes in consumer and industry needs versus demands, and shifts in the global economy and markets (FAO, 2014). This results in imbalances and leads to duplication of developmental activities, which often translates to failure due to resource use inefficiencies, which is prevalent in most South African sectors. The absence of integrated, sector-based approaches may increase the vulnerability of communities and livelihoods due to continued resource degradation and depletion (Nhamo et al., 2020a). Resources have been proven to have diverse allocations, needs and demands (Jacobs-Mata et al., 2021). The calculation of values and indices that show discrepancies and bias in resource use and allocation helps to curb the unsustainable use of critical resources such as water. This can be done through the Water-Energy-Food nexus tool, which helps to assess the availability, access and use of the water, energy and food sectors (Daher and Mohter, 2021). Biggs et al. (2015) and Mabhaudhi et al. (2019b) stated that WEF is a conceptual tool that has been introduced for use in the sustainable development of resources. Water resources in South Africa are key to livelihoods and development since water scarcity limits socio-economic development in semi-arid regions, while another factor, energy, is vital for economic development. Areas with drought challenges face resource gaps including access to water, food, energy and nutrition which are expected to increase with demographic conflicts and climate change, further leading to resource risks and vulnerabilities (Mohter et al., 2023).

6.2 BACKGROUND

Agricultural irrigation is the main user of water and worldwide accounts for about 70% of water withdrawal (FAO, 2014; Taguta et al., 2022; Nhamo et al., 2023). For commercial crops to gain optimum yield and quality, most need to be irrigated (Taguta et al., 2022; Shabalala et al., 2022). Food production Taruta and supply chain consumes about 30% of total energy consumed globally (FAO, 2014). Despite being South Africa’s second smallest province, Mpumalanga contains almost half of South Africa’s high potential arable land (Simpson et al., 2019). The Crocodile River Catchment is dominated by agricultural activities (rainfed and irrigated cultivation), forestry, and both rural and urban settlements. The middle region of the catchment is characterized by increased urbanization. The river flows through major towns such as Mbombela with mostly commercial farming activities (sugarcane, fruit and nut orchards and vegetable production), which are important characteristics of this catchment.

The research project aims to quantify resource use and efficiency in the main crops produced in the Mpumalanga Province. Macadamia is increasingly replacing many commercial forests and sugarcane in the area, and exponential growth has been seen in terms of area planted, gross value added and benefits from foreign earnings (Sibulali, 2020). Agricultural irrigation is the main user of water in terms of water extraction, demand and allocation, of which most goes to waste due to improper management (Mashabatu, 2022).

Macadamia nut production is a young industry, with South Africa being one of the dominant producers (Shabalala et al., 2022). An increase in macadamia orchards has been seen as an alternative to sugarcane in mainly KwaZulu-Natal and the Lowveld region of Mpumalanga. However, production is in areas of periodic drought and inadequate rainfall, meaning irrigation is essential (Shabalala et al., 2022). There is a word-of-mouth perception that macadamias use half the volume of water compared to crops such as sugarcane, with 89% of the farmers switching to the crop (Botha, 2018; SAMAC, 2020b). The crop is also known as less sensitive to water stress and would be a better industry competitor in terms of water productivity compared to other irrigated commercial crops. There is a lucrative potential for the crop in the export market and generation of foreign exchange. Exponential growth has been seen in terms of area planted, nutritional value, gross value added, and benefits from foreign earnings. As water is a scarce resource, the contribution macadamias can make using water during production needs evaluation. This is done to curb the use of critical resources such as water. The trade-off between the crops is investigated in this study. The project aims to quantify resource use and efficiency by the main crops produced in the Mpumalanga Province and to use the WEF tool to:

- calculate WEF nexus indicators for Crocodile River catchment in Mpumalanga,
- compare the resource use and efficiency of macadamia and sugarcane, and
- apply WEF indicators and LCA concepts using available crop data.

6.3 WATER IN THE CROCODILE RIVER CATCHMENT

The main use of catchment water is for irrigation of crops within the agriculture-food sector, followed by forestry and the ecological reserve. Of the surface water in the province, 75% is utilized for irrigation, 9% for electricity generation, 9% for mining and bulk industrial users, 9% for afforestation, and 8% for urban water usage (including 3% for rural use) (Simpson et al., 2019). The proportion of water utilized for irrigation in Mpumalanga is less than the average global agricultural water usage, which constitutes ~70% of freshwater supplies (Simpson et al. 2019). The other sectors where the demand for water is increasing include domestic and industrial use that were both less than 5% in 2010 (Table 0.26.1). The assurance of supply percentage values (Table 6.2) shows that the water available will continue to be insufficient to distribute to all the critical sectors as the demand exceeds the supply. Therefore the allocation of water is a sensitive operation and needs to be dealt with by the IUCMA on a quarterly basis together with the various water boards and other management structures across the wider Inkomati-Usuthu WMA. The water forums meet on a quarterly basis and have representatives from all the sectors concerned with and using water in each of the sub-catchments.

Table 6.1 Water sector information for the Crocodile River Catchment in 1994 (Bate et al., 1999)

Water Parameter	Units	Value
Mean annual precipitation	mm	880
Volume rainfall	10^6 m^3	8 614
Mean annual runoff	10^6 m^3	1 263
Dam capacity	10^6 m^3	198.51
Irrigated area	ha	154 296

Table 6.2 Water use sector demand and supply from the Crocodile River in 2010 (Jackson, 2014)

Sector	Demand	Supply	Assurance of Supply (%)
Irrigation	482.2	355.7	74
Domestic	46.3	43.8	95
Transfers	0.0	0	0
Industrial	26.6	26.6	100
Strategic	0.0	0	0
Afforestation	157.6	157.6	100
Alien Vegetation	32.1	32.1	100
Cross-border	50.5	50.5	100
Ecological Reserve	204.6	204.6	100
Total	**999.9**	**870.9**	**87.0**

6.4 CALCULATION OF WEF NEXUS INDICES FOR CROCODILE RIVER CATCHMENT

Data was collected to calculate important indicators for the Crocodile River Catchment in Mpumalanga as a major part of the Inkomati-Usuthu Catchment. As such, calculations have previously only been done at national or regional scale and some of the components of the indicators are not yet available at provincial or catchment level. Therefore, expert local knowledge was needed to make the necessary decisions on what values to use to achieve the best results. The preliminary results for calculated indices for water (Table 6.3), energy (Table 6.4) and food (Table 6.5) have been calculated for the Mpumalanga Province, focusing on the Crocodile River Catchment and in some cases on the Mbombela Local Municipality from the information currently available as given in the references.

6.4.1 Water indices

The SPIs calculated for the water sector give some insight into the status of the sector in Mpumalanga comparing the freshwater and availability with the demand at both catchment and household level (Table 6.3; Zarei et al., 2021). The proportion of available water resources was calculated as 198 m^3 per capita. This calculation was from data provided by Jackson (2014). The economic value of water is ZAR 23.86 per m^3 as stated by the Mbombela LM in 2021, but this may vary according to who is using the water – either for household use or by some industry or mining operations. The amount of stress on the catchment is at 87% when calculated as the available water supply divided by total demands across all sectors for 999.9 Mm^3 $year^{-1}$ compared to the 870.9 Mm^3 $year^{-1}$ available as supply. Jackson (2014) calculated the assurance of the water supply as 87% for IUCMA in 2010.

Table 6.3 Calculated water sector indicators to quantify WEF nexus interactions for the Mpumalanga Province

Indicator for Water	Units	Values	References
Proportion of available freshwater resources per capita (availability)	m^3 $capita^{-1}$	198	Calculated according to Jackson (2014)
Economic value of water	ZAR m^{-3}	23.86	Mbombela data (2021)
Water stress	%	87	Calculated for IUCMA in 2010- Jackson (2014)
Water requirement demand	Mm^3 $year^{-1}$	999	Calculated by Jackson (2014)
Proportion of households with access to water	%	91%	Simpson et al. (2019)

6.4.2 Energy indices

The total energy consumed in Mpumalanga in 2016 was 34 049 000 000 GWh (Table 6.4; Monyei and Adewumbi, 2017). The energy consumed per individual was 3200 kWh $capita^{-1}$ $year^{-1}$ (Monyei and Adewumbi, 2017). This data shows that sufficient electricity is provided to the population in the province. Some of this energy is distributed to the food sector, showing sector linkages. In Mpumalanga, sugar is considered as the most cultivated crop on an area basis and uses an estimated 130 602 234 kWh $year^{-1}$ (Pryor et al., 2017). However, this is only 3% of the total energy produced in the province (calculated in 2022). As Mpumalanga provides energy to the whole of South Africa, it can provide sufficient energy for its own population and food production.

Table 6.4 Calculated energy sector indicators to quantify WEF nexus interactions for the Mpumalanga Province

Indicator for Energy	Units	Values	References
Proportion of the population with access to electricity (accessibility)	%	90	Simpson et al. (2019), Monyei & Adewyumi (2017)
Energy (annual energy consumption) 2016	kWh $capita^{-1}$ $year^{-1}$	3200	Monyei & Adewumbi (2017)
Energy (farm gate)	kWh ha^{-1}	2 118	For sugarcane (Pryor et al., 2017)
Greenhouse gas emissions from energy generation	g CO_2 kWh^{-1}	900	Simpson et al. (2019)
Total electricity used for sugarcane	kWh yr^{-1}	130 602 234	Own calculation
Total Energy consumed Mpumalanga per year	kWh	34 049 000 000	Monyei & Adewumbi (2017)
Proportion of energy used for sugarcane	%	3.8	Own calculation
Residential energy use per year	GWh	12 530.03	Monyei & Adewumbi (2017)

6.4.3 Food and/or Agricultural indices

Sustainable Development Goal #2 is 'End Hunger, achieve food security and improved nutrition and promote sustainable agriculture'. The prevalence of poverty is one of the metrics used to measure the level of development within a country. It can be described as a lack of income and productive resources to ensure sustainable livelihoods, such as a lack of or limited access to food, safe drinking water, sanitation facilities, health, shelter, education and information (Ruch, 2014). Mbombela has in the past devised various means to curb poverty with initiatives such as job creation, support for small agricultural businesses, and implementation of 'Food for Waste' programmes (City of Mbombela, 2020). Food production flourishes when water, energy and land are abundant resources (Lawford, 2019) and is limited when these resources are scarce. Lawford (2019) states that food security is essential in order to sustain human societies and therefore needs to be promoted.

Agriculture was responsible for about 3.4% of Mpumalanga's total GDP of ZAR 269 863 million in 2013, which gives a GDP per capita for the province of ZAR 64 910 (Table 6.5; OECD Stats, 2018). The sector accounts for 4.3% of the gross geographical product (GGP) of the province and for nearly 12% of employment (StatsSA, 2011). Only about 19% of Mpumalanga's land area is used for agricultural production (Anonymous, 2012) of which Lotter (2015) states about 1 477 934 ha or 19.31% is cultivated land. Crops include maize, wheat, sorghum, barley, sunflower seed, soybeans, macadamias, groundnuts, sugarcane, vegetables, coffee, tea, cotton and tobacco, as well as citrus, tropical, subtropical and deciduous fruits. Fruits (tropical and sub-tropical), nuts and vegetables are a major contributor to the provincial and national export basket. There is still scope for expansion in this sector, both in terms of lands planted and downstream beneficiation (Anonymous, 2012).

Table 6.5 Food sector indicators to quantify WEF nexus interactions for the Mpumalanga Province (using sugar as the base crop)

Indicators for Food Sector	Units	Values	References
Food security	%	72.6	Simpson et al. (2019)
Water Footprint (sugar)	$m^3\ t^{-1}$	800	Le Roux et al. (2018)
Water requirement (sugar)	$m^3\ ha^{-1}\ year^{-1}$	9 000	Le Roux et al. (2018)
Water Use Efficiency (sugar)	$kg\ m^{-3}$	13.09	Calculated from Bate et al. (1999)
Total irrigation water for sugarcane	mm^3	524 136	Own calculation
Average sugarcane yield	$t\ ha^{-1}$	90	Pryor et al. (2017)
Cultivated land	%	19.3	Lötter (2015)
CPI: Weight for Mpumalanga		6.89 111.8	StatsSA (2021b) for 2019

6.5 WEF SUSTAINABILITY PERFORMANCE INDICATOR (SPI) CALCULATIONS

The Sustainability Performance Indicator (SPI) calculations will be used to illustrate the WEF linkages within the Crocodile River Catchment. The practical SPIs developed for each sector were calculated according to methodology used by Zarei et al. (2021). It was decided that one should have an equilibrium between the indices for each of the sectors, even though Zarei et al. (2021) had many more indices for the water sector. Therefore, as it is important to have a balanced approach, only three indices were selected per sector.

For water specifically in the case of this project, households with access to water were calculated according to Nhamo et al. (2021) with data provided by Simpson et al. (2019). The results show that there is adequate water for human use at household level from the municipality water reticulation system pipes (City of Mbombela, 2015). However, there are insufficient sanitation facilities despite water being available at most households (Simpson et al., 2019). The water stress index in the catchment is rather high meaning the catchment is not able to provide adequate water to the meet all the demands from each sector. Other representative indices that can be quantified include water quality. Such calculations from monitored values could be relevant in this research as the mining and other industries contribute to lower the water quality in the Crocodile River. However, the water was previously classified as Class C: Moderate quality (Palmer et al., 2013). Although irrigation of crops is beneficial for food production, the drainage water from irrigation reduces the water quality in the Crocodile River. These water quality concerns result in 16.5% of the households being subjected to polluted water (Simpson et al., 2019). Such indices could be useful in the future. Other SPIs about reliable water supply could not be calculated as there is insufficient input data at the correct time and spatial requirements to calculate them. As these are preliminary calculations, the search will continue for more detailed information to clarify some of these issues in the future (Table 6.6).

In terms of energy, the indices used by Zarei et al. (2021) are similar to those used by Nhamo et al. (2021) where the Energy Performance Index was calculated as the energy used per unit area or per capita per year. Greenhouse gas (GHG) emissions from energy generation activities account for about half of GHG emissions per farm, so in this case a value 0.55 was used (DEA, 2014).

For food calculations, Zarei et al. (2021) used a representation of the Food Security Index as often calculated by IFAD (International Fund for Agricultural Development) using the mean per capita supply of calories per day relative to the required calories, and the annual growth rate of calories per capita per day, together with other food production and consumption values. For this project, the Food Insecurity Index (FII) was calculated using the available statistics at a provincial level. In Mpumalanga Province, the statistics show that the proportion of the population that have adequate food is 72.6%, those with inadequate supply of food are 8.4%, and those under severely inadequate food supply are 19.0% (StatsSA, 2020). FII was taken as all those without adequate food supply, thus 27.4%. For the current calculation, the cultivated land was 1 477 934 ha as a proportion of the total land area of

Mpumalanga at 7 652 076 ha. The Cultivated Land Index (CLI) was estimated at 0.19 (Table 6.6) or just under 20% of land that is being used for food production.

Zarei et al. (2021) also suggested the calculation of a Price Index, which is the price of selected goods in a current period, compared to the prices of goods in a base period. As this is a commonly used index in RSA, the Consumer Price Index (CPI) was obtained for the Mpumalanga Province. In RSA, 2016 is usually used as a base year set at 100%, so one can expect the CPI to have risen since then. During 2019, the CPI was at 118%, and so a useful index for this will be 18% or 0.18, indicating that it has risen nearly 20% since the base year of 2016.

Table 6.6 Sustainability Performance Indicators calculated for Mpumalanga for 2014-2019

WEF Sector	Indicator	Index	References
Water	Water Stress	0.87	Calculated according to Zarei et al. (2021), data from IUCMA (2010)
	Households with water access	0.91	Calculated according to Nhamo et al. (2020a), data from Simpson et al. (2019)
	Water Efficiency Index	0.83	Jarmain et al. (2014)
Energy	Population with electricity access	0.90	Monyei & Adewyumi (2017)
	GHG Emission for energy use	0.55	GHG Inventory: 2000-10 (DEA, 2014) National GHG Inventory: 2017 (DFFE, 2021)
	% MP energy used in sugar	0.38	Calculated from Pryor et al. (2017)
Food	Food Insecurity index	0.27	Calculated from Simpson et al. (2019)
	Cultivated land index	0.19	Calculated from Simpson et al. (2019)
	Consumer Price Index – Mpumalanga	0.18	2019 data as increase from base 2016 = 1.0

6.6 CURRENT WEF RESULTS FOR CROCODILE RIVER CATCHMENT

The WEF nexus application was applied at Crocodile River Catchment level in order to obtain the synergies and trade-offs between the three different sectors. The preliminary results show that Mpumalanga, considered as a developing South African province (relative to Gauteng or the Western Cape), has an inadequate supply of water that does not meet the demand, with low levels of food insecurity amongst most of the population. However, there are some inconsistencies in the distribution of resources to these critical sectors, and this can be addressed by applying similar analysis for an urban area (e.g. Mbombela) and in a smaller catchment (e.g. Lower Komati) in future.

The indices were then combined into a spider diagram to show the balance between the various indices (Fig. 6.1).

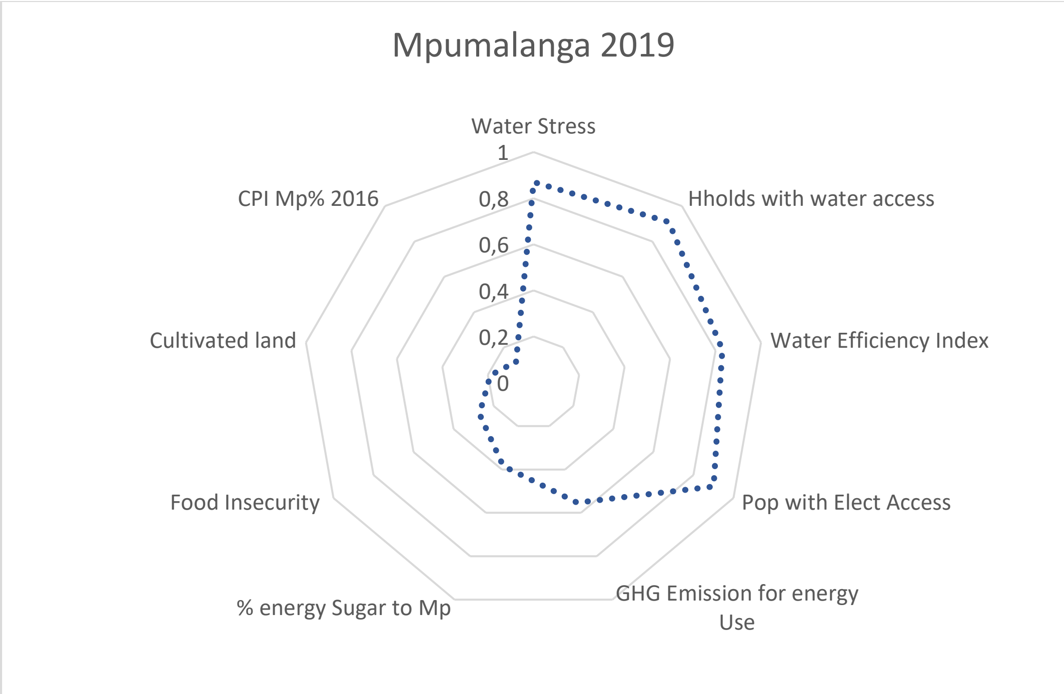


Figure 6.1 Spider diagram of WEF nexus Sustainability Performance Indicators to show the interlinkages in Mpumalanga in relation to water, food and energy for 2014-2019.

The water sector is facing challenges of increased demands from sectors such as mining and industry. Urban development or urbanization means that more water resources need to be diverted towards household use and human residential developments. The presence of the Crocodile River Catchment in Mpumalanga Province has meant that even though South Africa is water scarce, this important resource has been available in the region for food production using irrigation and for energy production via coal-fired power stations, both of which require large amounts of water. The proportion of water utilized for irrigation in Mpumalanga is less than the average global agricultural water usage. Currently, other sectors' water demands such as domestic use are nearly being adequately met.

The energy sector has contributed to improved livelihoods by supplying almost all domestic requirements, as more households have steadily been electrified. The issue of electricity consumption by the water and food sector will be studied in more detail in the future. The majority of energy in the Crocodile River Catchment is used by the industrial and transport sectors, with relatively little used for food processing. This is evident from the calculation of the use of only 3.8% of the province's total electricity in the sugar milling industry. The questions surrounding the use of clean and renewable energy are still a challenge as it is developing at a very slow pace. With time, the issue of the increasing prices from the main electricity provider in South Africa (Eskom) will become a disadvantage to the consumers who are mostly low-level earners.

The food sector index calculations have found that Mpumalanga is a food secure province with a low food insecurity index. Future work will compare this with the unemployment rate. The agricultural industrial sector only contributes low employment volumes that are partly seasonal (e.g. tropical and sub-tropical fruit harvesting) even though the GDP of the province is largely brought in through agricultural produce. The results show a low cultivated proportion of total land, low irrigation levels, and even low energy supply contributing to the production of food in the province. Therefore, there may be an opportunity for expansion of irrigated areas if there is sufficient water available. The proportion of cultivated land needs to be assessed considering the terrain, particularly the slope together with the suitability of land for a range of crops. This could also mean that the sugar produced and exported out of the province may not be directly beneficial to the communities of Mpumalanga. The application of the indices to other agricultural food products by comparison to the base crop of sugar will help the distribution of the resources, by not focusing only on sugar production but to expand the analysis to other food crops such as macadamia nuts, fruits and vegetables.

6.7 WEF AND LCA INDICES FOR MACADAMIA AND SUGARCANE

6.7.1 Information about macadamia production in South Africa

Macadamia nut production is a young industry, with South Africa being one of the dominant producers (Shabalala et al., 2022). The country was noted as a top producer in the years 2011 and 2013-2015, surpassing Australia, planting at a rate of over 600 000 trees per year and producing 13 146 metric tonnes of kernel nuts in 2015 (Parshotam, 2018). National data in 2018 stated that with more than 7.5 million macadamia trees and 2 000 hectares added every year, production is soon expected to double. According to the Southern African Macadamia Growers Association (SAMAC), new macadamia tree planting in South Africa has tripled in the last 4 years from 1 250 ha in 2013 to 3870 ha in 2016, with planting almost doubling between 2015 and 2016 from 2000 ha to 3 870 ha. South Africa's macadamia industry is expanding by over 3 000 ha/year and the planted area has reached around 30 000 ha. Currently there are 28 000 ha of established macadamia orchards with the largest growing region being Mpumalanga followed by Limpopo and KwaZulu-Natal. Macadamias can be sold as nuts in shell or kernel nuts only. Increasing export prices seem to be the main attraction for most smallholder grower interests in the macadamia sector (Parshotam, 2018). According to SARS, the total value of South African macadamia nuts sold in 2019 was R4.8 billion, with kernel nuts being the biggest income generator and more than 98% of South Africa's macadamia produce destined for export markets (SAMAC, 2020a).

Macadamia has threats like any other crops such as drought and extreme temperatures (Bandason et al., 2021). It is, however, known as less sensitive to water stress and would be a better industry competitor in terms of water productivity compared to other irrigated commercial crops. There is a lucrative potential for the crop in the export market and generation of foreign exchange. Exponential growth has been seen in terms of area planted, nutritional value, gross value added and benefits from foreign earnings. Bandason et al. (2021) suggest that macadamia can be integrated with annual crops to improve livelihoods and can be used as a strategic cash crop in the wake of climate change in order to curb the use of critical resources such as water.

6.8 CONCLUDING REMARKS

The WEF nexus indices have been evaluated for Mpumalanga Province focusing on the Crocodile River Catchment by using data available from previous publications. From the food indices, it can be seen that Mpumalanga is a food secure province although its main agricultural production is sugarcane and sub-tropical fruits and nuts. These commodities are exported out of the province so may not be directly beneficial to the communities of Mpumalanga.

There is a high proportion of the population that has access to electrical power, which is good as much is generated from the coal mining in the Highveld region of the province. However, a low percentage of the provincial energy consumption goes to the milling and processing of sugar, with the majority going to the industrial and transport sectors.

Water as an important resource is available for food production using irrigation as well as for energy production from coal-fired power stations. However, there is increasing demand for water from the municipalities for domestic use, and this could result in conflict between the sectors. The WEF indices show high values for the population with access to water and a high-water efficiency index, but also a high-water stress index.

Furthermore, detailed calculation of the WEF indices is necessary as due to the lack of specific data for the same time slices, it has been difficult to do comparative calculations. Some of the information available at the provincial level is only from 2014 to 2019 and not for the current periods. Therefore, it was difficult to compare the data available about population changes from StatsSA with other available information.

Another compounding factor is the different spatial boundaries. As most of the reporting is done at a provincial or district municipality level, it is difficult to align these values with the boundaries of the river catchments. Therefore, further attempts to link the water and food production with the spatial distribution of the land use from remotely sensed information may prove to be more profitable.

CHAPTER 7: QUALITATIVE PARTICIPATORY ENGAGEMENT RESEARCH FOR CROCODILE RIVER CATCHMENT

7.1 INTRODUCTION

This chapter summarizes the findings of the qualitative participatory engagement research conducted including a Participatory Scenario Development (PSD) process, a communication questionnaire, a series of semi-structured interviews, two focus group discussions (FGDs) and a series of other stakeholder consultations (meetings, briefings, presentations, etc.). The semi-structured interviews provided scoping information for the broader WEF nexus stakeholder group in the case study areas. This was then followed up with a PSD process to understand how stakeholders collectively engage on future development scenarios related to the WEF nexus. Two virtual FGDs were later held with stakeholders working in the catchment, largely to triangulate the interview and PSD results. In addition, a questionnaire was developed to ascertain the most appropriate channels and formats to use when communicating the WEF nexus concept, purpose and use in informing decision-making to diverse stakeholders.

In addition to the field research activities mentioned above, stakeholder meetings were also held as and when needed. These meetings were differentiated from the semi-structured interviews in that they were not recorded, and no consent was provided. As such, the content of these meetings has not been included in the formal analysis but they were rather used as reference points for identification of other respondents and/or sources of secondary information.

Recognizing the importance of conveying scientific concepts in everyday language without excessive jargon, the team made efforts to formulate scientifically accurate messages using simple language. This was particularly crucial given the significance of water and the potential conflicts it can generate among individuals and organizations. To address this, a survey was conducted to assess people's understanding of science communication. Innovative approaches were developed to explain the concepts and deliver clear messages, especially in rural areas where English may not be the primary language. Two methods were employed to communicate the messages of the WEF nexus and its impact on personal everyday life. These included using a visual illustration of a bucket of water and a diagram depicting water users across the catchment, highlighting key features and the dilemma faced by those responsible for allocating limited water resources to users.

7.2 SEMI-STRUCTURED INTERVIEWS

A semi-structured interview guide was developed as the first qualitative data collection instrument (Appendix 1.1). The purpose of the interviews was to understand the types of decision-making that takes place in the catchment, who is affected by those decisions, and who is responsible for taking them. The project team carried out a combination of group and individual expert interviews. Interviewees included government officials, academics and migrant farm labourers, with consideration for age and gender balance (Table 7.1). The selection of stakeholders to participate in the interview process was done through close consultation with Inkomati-Usuthu Catchment Management Area officials. Participation in the interviews was voluntarily and the researchers ensured the maintenance of confidentiality throughout the research process.

The first round of interviews comprised 15 participants, of which 33% were female and 67% male (Table 7.1). The local government officials interviewed made up 53% of the total number of interview respondents, with 25% being female and the majority (75%) being male. One female farmer was interviewed (7%). Industry and parastatal representatives comprised 13% and 27%, respectively, of the total respondent population (50% males and 50% females). This does reflect a bias to views from government representatives. In addition. the active participation and fair representation of women in decision-making structures or any other policy-making process is a clear gap, and the sample size reflects this. If the results in Table 7.1 provide a representative picture, it shows that women remain relatively unrepresented in economic structures, despite the fact that South Africa's Constitution sets out gender equality as a founding principle, especially in decision-making structures.

Table 7.1 Gender of respondents in the different sectors

Sector	Female	Male	Total
Farmers	1	0	1
Local government departments	0	3	3
Industry	0	2	2
Municipality	2	3	5
Parastatals	2	2	4
Total	**5**	**10**	**15**

From Table 7.2, it is evident that most interview participants reside in Mbombela Local Municipality. Of the 11 interviewed participants residing in Mbombela, 45% work for the municipality, 27% are from government departments (excluding the municipality) and 27% are from parastatals. Only 2 participants interviewed reside in Nkomazi LM (one from industry and the other from a parastatal). Lastly, one participant was interviewed who resided in the Bushbuckridge LM (namely a farmer) and one lived in Johannesburg (parastatal). From this analysis, it can be concluded that the spatial representation of interviewed participants is biased towards Mbombela which is the main city within the Crocodile River Catchment that is the focus of this study and is 70% urban.

Table 7.2 Sector analysis of respondents according to municipalities

	Local Municipality				
Sector	**Bushbuckridge**	**Mbombela**	**Nkomazi**	**Johannesburg**	**Total**
Farmers	1	0	0	0	1
Government	0	3	0	0	3
Industry	0	0	1	1	2
Municipality	0	5	0	0	5
Parastatals	0	3	1	0	4
Total	**1**	**11**	**2**	**1**	**15**

7.2.1 Analysis of semi-structured interviews

The aim of the interviews was mainly to collate views from numerous stakeholders using a semi-structured questionnaire on how various decisions are made in terms of the use, distribution and/or development of water, energy and food. Specifically, it explored the decision-making process in the Inkomati-Usuthu Water Management Area. The outputs of this project are expected to provide integrated solutions that support the decision-making of the complex relationships among sectors, water management and distribution throughout the Inkomati-Usutu Catchment. From the analysis below, it can be concluded that water scarcity in South Africa is largely attributable to physical causes exacerbated by insufficient water infrastructure maintenance and investment, the impact of global climate change, climate variability and increasing demand for available water resources. The sub-catchments have experienced water shortages over the last decades. Stakeholders reckon that the water shortages are induced mainly by the demand from different sectors (agriculture, industry and the municipality) within the sub-catchments, hence, rationing of water was at times executed during peak hours.

In terms of stakeholder engagement, most stakeholders believe that key experts are engaged in decision-making in the sub-catchments, via the quarterly forum meetings. This analysis concurs with Nhamo et al. (2020b), who gave credence to stakeholder buy-in as instrumental in breaking the silo-mentality in decision-making. They further argued that stakeholder participation facilitates cross-sectoral convergence and coherence in resource management, more especially in the era of resource scarcity and climate change. However, stakeholders still believe that key development priorities in decision-making within the sub-catchments are politically motivated. Intrinsically, decisions made should be in the interest of stakeholders ensuring that the needs of society are satisfied optimally.

Challenges faced by the different dimensions in the WEF nexus
Considering the stakeholders' opinions on the factors that influence decision-making, 87% believe that key water decisions are made in isolation in each of the sub-catchments. Water availability has been an issue in the catchment, with 50% of the participants who strongly agree and 36% who agree that this indeed poses an issue for the catchment (Fig. 7.1). Due to the problem of water availability, 74% of the interviewed stakeholders believe that there are municipal induced water shortages in the catchment. On the other hand, 67% believe that water shortages are induced by industrial activities, and lastly, 80% believe that water shortages are induced by agricultural activities in the sub-catchments (Fig. 7.1). This shows a diversity of opinions across the stakeholder groups with many believing that water shortages are due to more than one sector, so perhaps this needs to be unpacked further in future stakeholder engagements. As such, most stakeholders (94%) indicated that they expect there to be water shortages in the sub-catchments in future. The prediction is that the Inkomati-Usuthu Catchment will possibly become drier as South Africa experiences the reality of climate change.

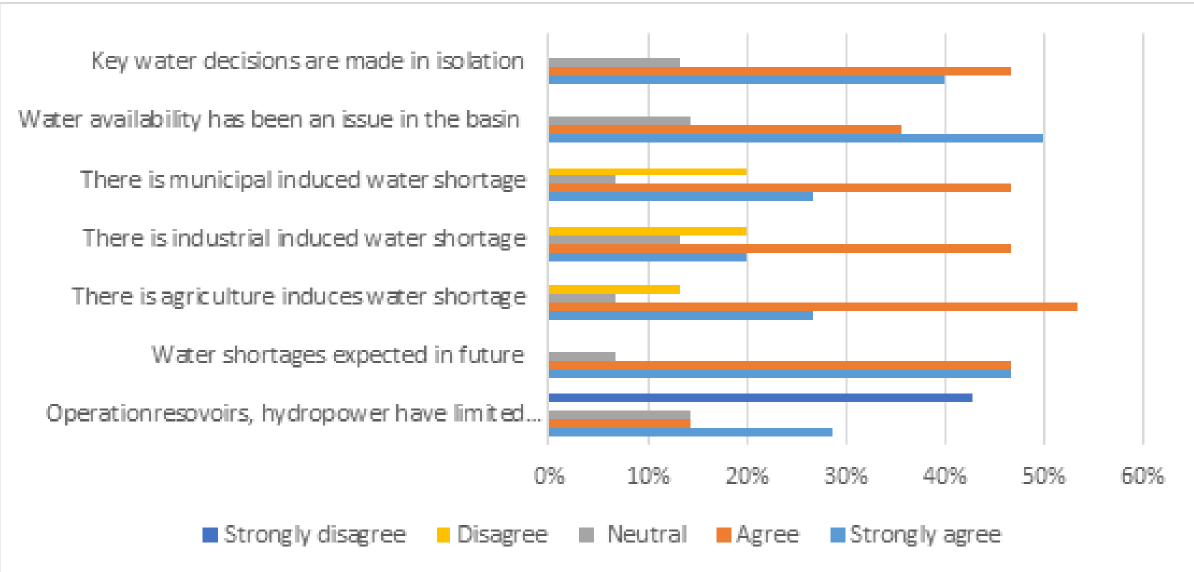


Figure 7.1 The extent to which stakeholders agree or disagree with each statement.

Stakeholder participation in the decision-making process in the IUCMA
The interview results also provided insights on stakeholder engagement for decision-making within the Inkomati-Usuthu Catchment area. As depicted in Fig. 7.2, it is evident that key development priorities are politically motivated (60% agree and 7% strongly agree). Many stakeholders also believe that development and climate scenarios as well as the stakeholders concerns are considered in decision-making in the sub-catchments. There appears to be the full range of opinions about whether stakeholder feedback is sought to ensure relevant decisions are made, from strongly agree to strongly disagree.

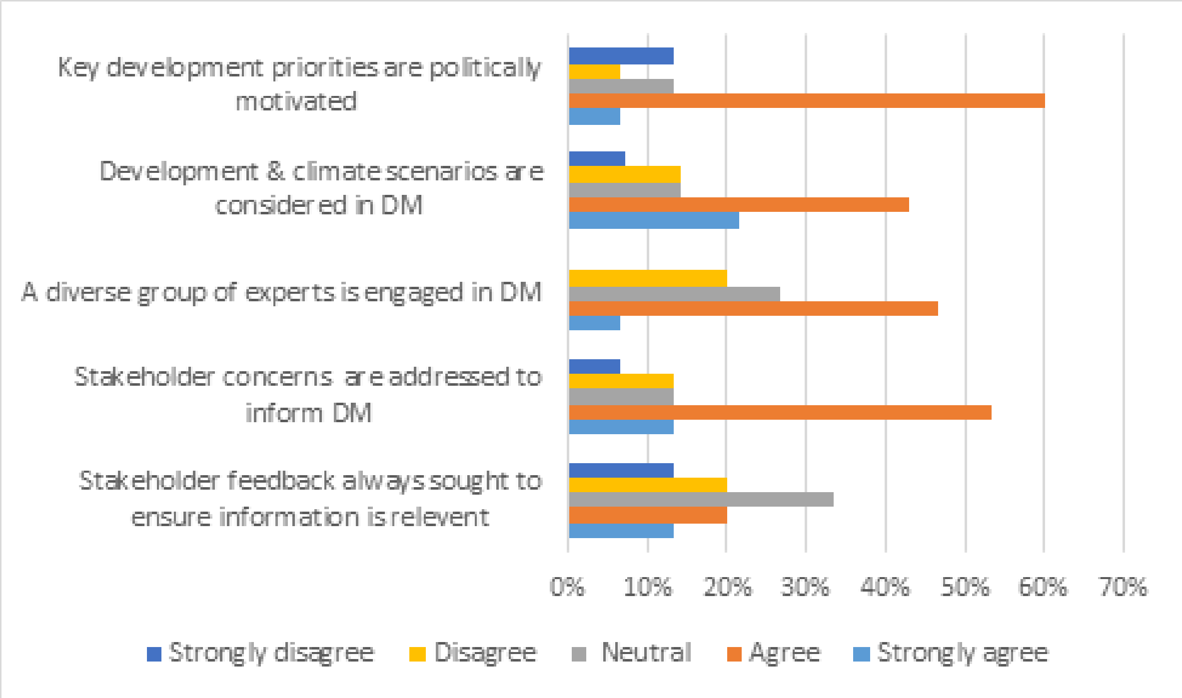


Figure 7.2 Stakeholder engagement responses about decision-making (DM) in the IUCMA

In addition, the analysis shows that many respondents (54%) in the sub-catchments believe that a diverse group of experts are engaged in decision-making. Roughly 66% of the interviewed stakeholders highlighted that their concerns are addressed to inform decision-making in the sub-catchments. This means that in the catchment, respondents believe that their views are heard and considered during decision-making. Conversely, only 33% believe that stakeholder feedback is sought to ensure information is relevant for decision-making in the sub-catchments. This could imply that while they feel they are adequately engaged through forum meetings, workshops, and other engagement processes, there is no feedback loop to demonstrate that their inputs are in fact considered in the decision-making process, nor to ensure that information gathered by a participatory engagement process was in fact a true reflection of stakeholder inputs.

Agricultural innovations for improved WEF nexus efficiency

Interview respondents were then asked a series of questions to demonstrate their opinions on how different elements of the WEF nexus are interrelated. As per Fig. 7.3, many respondents (71%) agree that energy production, such as hydropower or cooling, influences water-related ecosystems. Roughly 87% of the respondents further agree that an increased water supply would require increased energy for pumping. Further analysis shows that most stakeholders (80%) agree that increased agricultural activity influences water quality, although 13% disagree. A resounding 94% (agree and strongly agree) believe that increasing agricultural production will require increased water use efficiency, while 7% of the interviewed participants disagree. This makes sense in irrigated agriculture because increased water use efficiency mitigates water shortages, and as such, more water will be available for irrigation, resulting in higher production. Lastly, 86% of the participants agree that agricultural products and waste can be used as a source of sustainable energy. This is consistent with the views expressed in the PSD exercise on the importance of promoting a circular economy in the catchment.

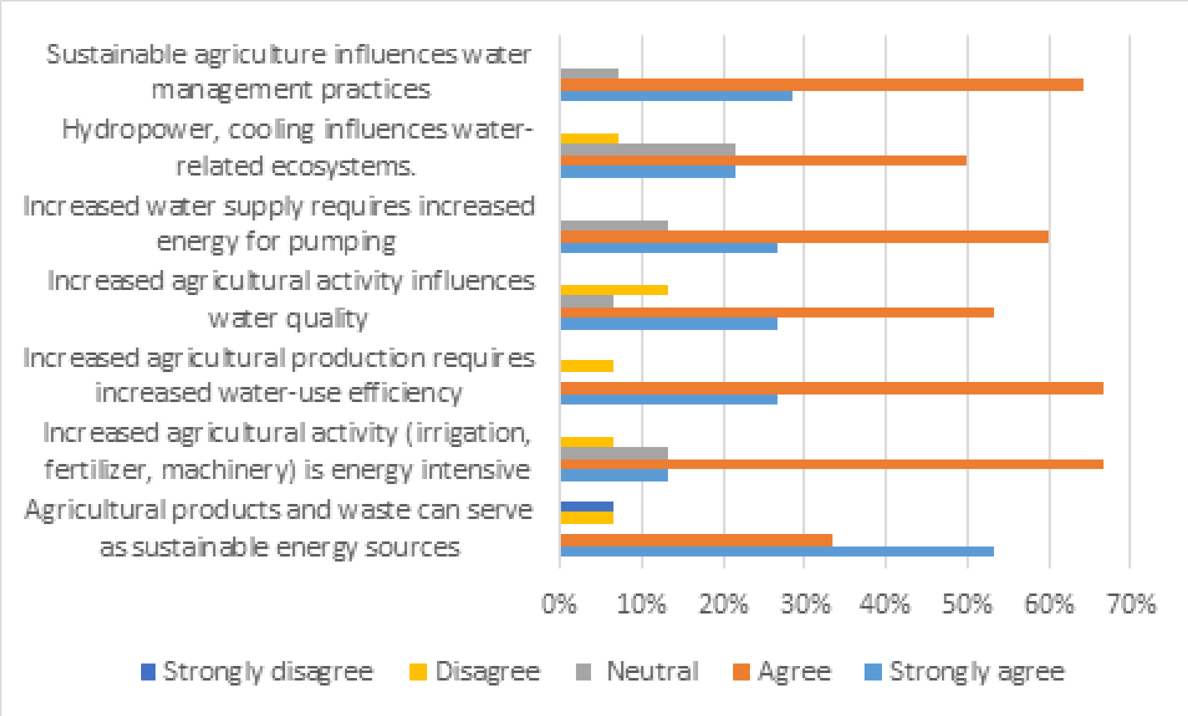


Figure 7.3 The extent to which stakeholders agree on agricultural innovation

7.3 PARTICIPATORY SCENARIO DEVELOPMENT

The second qualitative data collection method used was Participatory Scenario Development (PSD). PSD is a critical approach in guiding decision-making within the complex realm of the water-energy-food nexus. By involving a diverse range of stakeholders, PSD fosters collaboration and mutual learning, while also ensuring the diverse perspectives and insights of those who interact directly with these systems are integrated into the development of scenarios. In the intricate web of interdependencies that link the water, energy and food sectors, scenarios that lack holistic, ground-level insight risk perpetuating inefficiencies and exacerbating resource stresses. Therefore, PSD is pivotal in surfacing nuanced understandings of system dynamics and potential leverage points. Through exploring a range of possible futures, it not only aids in anticipating challenges and opportunities, but also contributes to the creation of robust, adaptable strategies that can effectively navigate the uncertainties inherent in these interconnected domains.

The PSD approach was used in the early stages of the project to engage with stakeholders in the catchment. Other workshops and FGDs with stakeholders in the WMA were also conducted in a consultative manner, i.e. primary data collection of lived experiences. Several consultative sessions were conducted throughout the lifespan of the project to:

a) Introduce the WEF nexus concept, map out actors and institutions, define current issues about the nexus, and create initial scenario narratives.
b) Unpack and develop WEF nexus scenarios in the WMA. A multi-stakeholder workshop was conducted in November 2020 with 30 people attending, including 11 from government organizations, 9 from the private sector and 5 from parastatals (excluding the project team and organizers). Stakeholders from diverse backgrounds attended with representatives from agriculture, education, environment, water and sanitation and private sector industries.

The project team used a PSD approach to engage with different sub-catchments of the IUWMA on WEF nexus development trade-offs. This qualitative and participatory technique aimed to encourage discussion, deliberation and the exchange of thoughts and ideas. The purpose was also to facilitate the framing and re-framing of perceptions of problems, resulting ultimately in greater social learning (Patel et al., 2007). Several arguments in favour of participation in scenario development have been put forward in the literature (Volkery et al., 2008; Patel et al., 2007; Stirling, 2007), including that participation helps to:

- support the democratic rational for intrinsic social desirability of equity of access, empowerment of process, and equality of outcome, with the aim of countering the exercise of power;
- give access to practical knowledge and experience, learn about new problem perceptions while identifying new challenging questions;
- gather diverse, extensive and context-specific knowledge to take more careful and explicit account of divergent values and interests;
- bridge gaps between the scientific communities and governments, businesses, interest groups and citizens, thus providing a reality check for research assumptions and methodology; and
- improve communication between scientists, decision-makers and stakeholders and facilitate collaboration and consensus building on problem solving.

The process of PSD was therefore conducted in a consultative manner through workshops and focus group discussions with stakeholders in the WMA to:

- introduce the WEF nexus concept, map out actors and institutions, define current issues pertaining to the nexus, and create initial scenario narratives; and
- unpack and develop WEF nexus scenarios in the WMA with stakeholders.

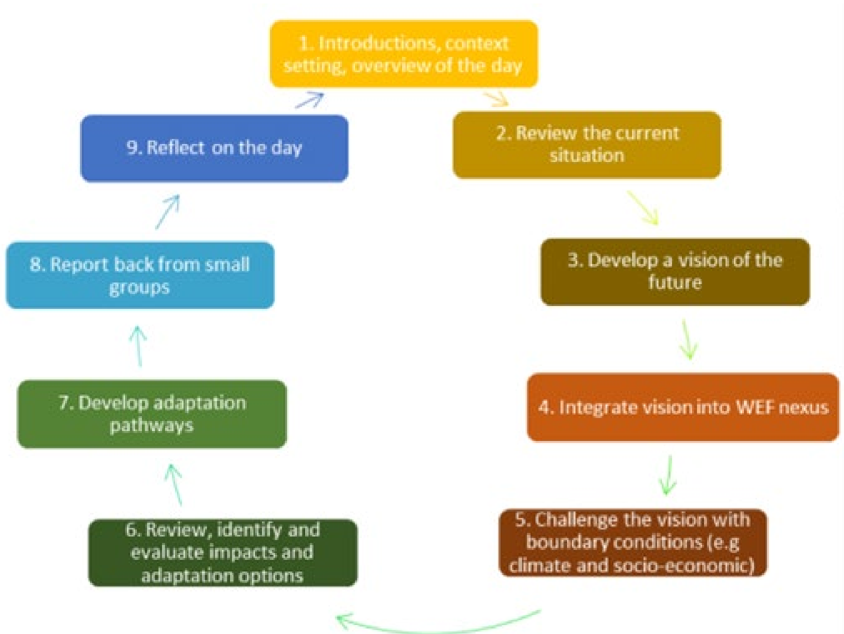


Figure 7.4 Participatory Scenario Development (PSD) process diagram

The key steps followed during the PSD workshop are illustrated in Fig. 7.4 and summarized below.

1. **Introductions, context setting and overview of the day:** The workshop opened with an introduction to the overall focus of the workshop and a detailed review of the planned activities. A short free-flowing discussion followed on what key issues stakeholders face in the WMA.
    a. What are some defining features of the WMA – differences between sub-catchments?
    b. Who are the key role-players and decision-makers?
    c. Who are the key users of water and energy?

2. **Review of the current situation:** Participants were then invited to discuss the driving forces of current development within their WMA, including agricultural change, urbanization and use of natural resources. Depending on the perceived magnitude of current climate-related issues, key drivers of change often include existing levels of flooding, drought and extreme weather events. From this, key sectors and/or geographic regions of greatest concern to participants, considering current and future changes in climate, were identified:
   a. What are the major drivers of development in the WMA currently? Think of agricultural development, mining, urbanization, use of natural resources?
   b. What are the key drivers of change? Think of drought, flooding, climate change, extreme weather events, etc.? Potential changes in planned policies and interventions.
   c. Discuss regional variation within the sub-catchment.
   d. Different scenarios will be formed at this point. A typical starting narrative is the business as usual (BAU) scenario, whereby the key drivers affecting future development are on-going demographic trends, such as population growth, economic growth, and increasing urbanization. Other scenarios may be based upon the implementation of planned national polices and interventions, or on certain climate change projections.
3. **Develop a vision of the future:** Participants were then divided into groups based on economic sectors (e.g. forestry, fisheries, agriculture, water) and asked to develop a detailed future vision of their sector using their expert and/or local knowledge (for example, Kok et al., 2006; Fig. 7.5). Participants were encouraged to develop their desired futures *without* specific consideration of climate change but rather their knowledge and awareness of all development trends and challenges in their targeted region or sector.
   a. Co-develop a sector vision for 2050.

Figure 7.5 Group discussion during PSD in Mbombela in November 2020.

4. **Integrate sector-specific visions in WEF nexus scenarios:** Different break-away groups (Fig. 7.6) were then formed by mixing participants from different sectors to discuss each of the scenarios identified in 2 (e.g. BAU, policy change, climate change, socio-economic change) with a representative from each sector in each group. Sector-specific visions were shared and integrated under each scenario. Participants explored how the integration of sectors impacts on sector-specific visions, with the added layer of the specific scenario (BAU, political/policy change, climate change, etc.). A revised vision was then discussed under each scenario.
   a. Paint a picture of the scenario and its impact on sector visions. Can they be realised or not?
   b. What are the opportunities for integration?
   c. What are the challenges?
5. **Using a process of back-casting,** participants then worked backwards from their future WEF nexus state and scenario, identifying a series of broad steps that could be used to achieve the WEF nexus vision (Robinson, 2003).

a. Once the vision has been articulated, identify steps (back-casting) on how to achieve it between then and now.

The following steps were not fully conducted in the multi-stakeholder workshop held in November 2021 due to lack of time but follow-up engagements were held to address them:

Figure 7.6 Group discussion and presentations during PSD in Mbombela, November 2020.

6. **Identify, review and evaluate impacts and adaptation options:** Continue working with each WEF nexus scenario, and have participants focus on identifying adaptation options to reduce or minimize any adverse impacts, as well as strengthen any positive impacts. Recommended adaptation options are meant to increase the resilience of created pathways under the constraints. If the impacts are considered too severe within a particular scenario, the scenario is considered unsustainable (i.e. not resilient enough in the context of the impacts over the applied time horizons). With a horizon of 2050, short-term measures are those required within the next 5 years (up to 2025), medium-term horizons are those required within the next 10-15 years (up to 2035) and the long-term horizon are those measures required up to 2050.
7. **Develop adaptation pathways:** After identifying adaptation options, groups should then focus on extracting a series of actions that stakeholders deem to be crucial for the future resilience of each scenario in the context of projected socio-economic and climate change. These actions could include the adaptation options identified in the previous step, but also the elements of the created future scenarios important for the overall resilience of the scenario. During this step, the actions across all the groups will be compiled to create a set of actions that are robust across all different scenarios. The participants are then asked to identify short-term priorities linked to current or ongoing initiatives within the WMA that they were aware of, followed by recommended actions that are needed to achieve the longer-term goals.
8. **Reporting back from groups and discussion:** In this session, participants present their prioritized adaptation options at different time scales as developed in their groups. The purpose of the session is to create integrated adaptation pathways to demonstrate priority interventions across scenarios. Participants are then encouraged to cluster similar actions and explore synergies and minimize trade-offs in related sectors such as agriculture, water management and food security.
9. **Plenary discussion and reflection on the workshop:** The final session provides opportunities for the participants to reflect on the process and discuss issues that emerged during the workshop.
   a. What were the highs and lows of the workshop?
   b. What was as you expected? What surprised you?
   c. How would you rate your agency's ability to inform/change decision-making in the sub-catchment?

7.3.1 Review of the current situation

Participants listed defining features of the WMA as (Fig. 7.7):

- Key industries: mining, agriculture, and eco-tourism, which emphasize issues of sustainability and seasonality. The fruit industry faces particular challenges of competitiveness.
- The National Water Act of 1998 is not being implemented. Specifically, water rights are not used optimally.

- A well-endowed catchment in terms of rainfall, but lack of storage capacity in the catchment.
- Water infrastructure is also not being maintained.
- The catchment experiences a growing demand for water supply due to its growing population.
- The catchment has experienced wetland encroachment in many parts.
- Water pollution is problematic and linked to activities such as illegal dumping, mining and poor urban sanitation.
- There is a lack of awareness of environmental conservation and its importance, and that several parts of the catchment are sensitive ecological areas.
- There is a sense of community in many parts of the catchment.
- Dis-functional waste water treatment.
- While leadership is lacking at the local government level, the catchment boasts strong institutions, e.g. functional Catchment Management Agencies (CMAs) and Catchment Forums (CFs).
- The province now has a university, which contributes to capacity strengthening in the area.
- Powerful traditional leaders.
- Most policies are in place for energy and climate.

Figure 7.7 Word cloud depicting participants' inputs on drivers of change in the catchment.

7.3.2 Future scenarios

Based on the defining features and drivers of change, four scenarios emerged (Fig. 7.8).

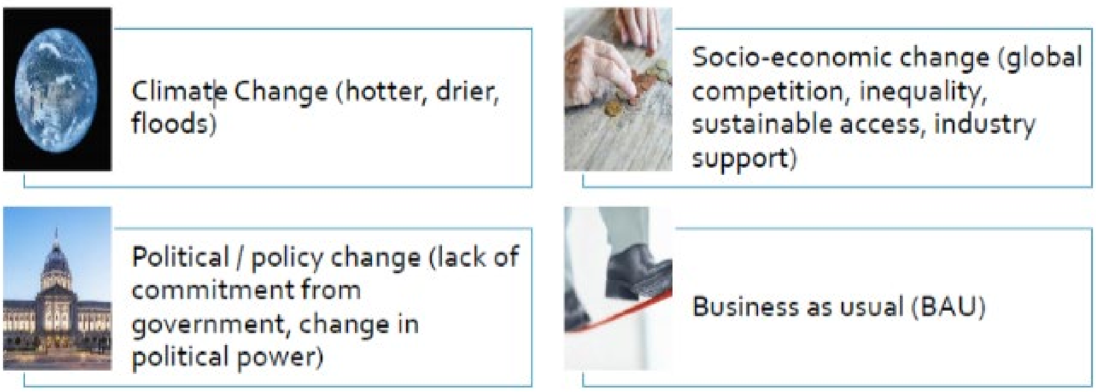


Figure 7.8 Scenarios developed in the PSD process.

Scenario 1 "Adapt and Thrive – Agriculture in the Climate Crisis of 2035" (characterized by climate change – hotter, drier, floods)

The year is 2035. Climate change has accelerated, bringing increasingly hotter and drier conditions. Unpredictable floods wreak havoc in the WMA, laying waste to the infrastructural landscape, and droughts become the norm, threatening agriculture and hence food security. Concurrently, the social impacts of climate change are dire, with an uptick in disease outbreaks, escalating health costs, and social instability. Despite these challenges, a resilient agricultural sector emerges, having adapted to the new normal and finding innovative ways to sustainably increase agricultural outputs and jobs by 10%.

Agricultural Transformation – Climate resilient crop species become mainstream. In response to the changing climate, farmers transition from traditional crops to more robust, drought-resistant and heat-tolerant varieties. Genomic technologies play a crucial role in accelerating the development and distribution of these crops.

Chemicals, previously seen as a scourge, become a critical tool in combating increased pests and diseases outbreaks. They are now more sophisticated and environmentally friendly – thanks to advancements in green chemistry and biotechnology.

Technological adaptations are witnessed across all sectors. The use of AI and Big Data analytics are widespread, helping farmers to monitor crop health, predict diseases, optimize irrigation, and increase overall productivity. A new generation of farmers emerges, trained not just in traditional farming techniques, but also in the use of these technologies.

Water Management Strategies – Water scarcity becomes a grave concern due to the hotter, drier conditions and the increasing demand from agriculture. This necessitates the adoption of efficient water management strategies.

Massive investments are made in water storage facilities, desalination plants, and the restoration of natural water systems. Drip irrigation and other precision agriculture technologies become common, ensuring that every drop of water is used efficiently.

Animal Husbandry Adaptations – Animal husbandry also undergoes transformations. Climate-resilient livestock breeds become popular, and technological solutions such as IoT devices for real-time health monitoring are employed to ensure the wellbeing of the animals in harsher conditions.

Mitigation Implementation and Disaster Relief – The funds for mitigation implementation and disaster relief skyrocket. Governments, international organizations, and private sectors form strategic partnerships, pooling resources to mitigate the impacts of climate change and respond to disasters in a timely and efficient manner.

Infrastructure Improvements – Climate-resilient infrastructures are built in the WMA. These include flood-resistant roads and bridges, resilient energy systems, and agricultural facilities designed to withstand extreme weather conditions. Infrastructure development adopts a "build back better" approach, ensuring all new builds are resilient to future climate conditions.

Policy Changes – Climate change adaptation becomes mainstream in all sectors, leading to substantial policy changes. Climate considerations are integrated into every facet of public policy, from education and health, to economic and urban planning. Governments work hand in hand with scientists, technologists, and local communities to ensure these adaptations are sustainable and beneficial for all.

In conclusion, the year 2035 presents a vastly different WMA, one that has been fundamentally reshaped by the realities of climate change. But it's a world that is not only surviving – it's a world that is learning, adapting, and persisting in its efforts to thrive.

Scenario 2 "The Emergent Era – A Socio-Economically Transformed 2050" or "The Global Market Frontier of 2050" (characterized by socio-economic change, global competition, inequality, sustainable access, industry support)

In the year 2050, global socio-economic change is the rule rather than the exception. The world is defined by intense global competition, rising inequality, and sustainable access challenges. However, a reimagined landscape emerges from the quest for industry support, new intergovernmental collaborations, and improved compliance standards.

Industry Transformation – The industry of 2050 is a space of high global standards and intense competition. The cost of compliance with international regulations poses a significant challenge, yet it also catalyses industries towards innovation and improvement. Partnerships and collaborations become the lifeline of the industry, with government subsidies aiding their growth and allowing them to compete on a global scale.

Water Management – In response to increased water demand and environmental degradation, Memorandums of Understanding (MoU) are signed with other countries, establishing a framework for collaboration and sharing of resources. The review of water rights allocation ensures equitable distribution, and efficient use is promoted through technological advancements.

Energy Sector – The energy sector, once a key contributor to pollution, now leads the way in compliance with high environmental standards. A significant shift to renewable energy reduces carbon emissions, while improved environmental management ensures the responsible allocation of water resources for energy production.

Urban and Municipal Developments – Urban and municipal infrastructure faces immense pressure due to population growth and rapid urbanization. However, the municipalities respond with resilient infrastructure developments, creating an environment conducive for all sectors to thrive. Local Economic Development (LED) plans are deployed to balance market competitiveness and ensure socio-economic development.

Agriculture – Agriculture faces a dichotomy between commercial and subsistence farming. Commercial farming finds it easier to comply with global standards, while subsistence farming struggles due to market limitations. However, interventions are put in place to bridge this gap, such as improved access to farm implements, enhanced research and technology, and initiatives aimed at improving market access for subsistence farmers.

The local market sees a resurgence, with imports gradually replaced by locally produced food, improving food security.

Enforcement and Compliance – Efforts are made to align with Sub-Saharan standards, setting the tone for regional cohesion and competitiveness. Enforcement of compliance becomes crucial to ensure the equitable and sustainable functioning of all sectors.

Policy Review and Government Processes – To facilitate these changes, a major policy review is undertaken. Government processes and systems are streamlined to encourage the private sector, facilitate intergovernmental relations, and support industry.

The year 2040 witnesses a global socio-economic shift with enhanced cooperation and competition. Although challenges persist, the world adapts and evolves, driven by collective effort and an unwavering commitment to sustainable growth and development.

Scenario 3 "The Governance Imbalance of 2050 – The Fractured Nexus" (characterized by political/policy change, i.e. a lack of commitment from government, and change in political power)

In 2050, a series of political upheavals and policy changes have resulted in a lack of government commitment, triggering a ripple effect across the water, energy, and food nexus in the catchment and the country at large. The country now faces the consequences of these decisions.

Political Impact and Legislation – Politics, the creator of legislation, undergoes dramatic shifts in power. These shifts result in new laws and exemptions that affect every sector.

In the water sector, the assignment of water rights becomes unpredictable and biased, leading to inequitable access and unsustainable use of this vital resource. Exemptions are often granted based on political affiliations and vested interests rather than legitimate needs, leading to further disparities.

The industrial sector faces regulations that seem to favour certain corporations over others, often those with closer ties to the governing powers. The new rules around water use and rehabilitation are skewed, leading to increased pollution and degradation of water bodies.

Agriculture, a sector already reeling from climate change, is hit hard by the lack of government commitment. The assigning of rights and exemptions for water usage becomes an arduous process. Compliance with the new rules becomes a herculean task, especially for small-scale farmers.

International vs Local Collusion – In this new era, a dangerous trend of international versus local collusion emerges. Legislation is manipulated and bent to favour foreign agriculture export markets, often at the expense of local businesses and communities. This collusion disrupts the local economy and aggravates socio-economic inequalities.

Municipalities and Land Use – Municipalities are forced to make drastic changes in land use due to the new legislation. However, compliance and exemptions are largely influenced by political pressures rather than local needs or environmental considerations. This leads to poorly planned urbanization, destruction of green spaces, and increased strain on local resources.

Political Level and Governance – Political self-interest and lack of transparency become rampant. Compliance to governance procedures is often sidestepped due to political pressure. The dominance of political party governance overshadows the needs of the public. Secrecy takes precedence over transparency, leading to political extortion and public disenchantment.

The year 2050 is a country and catchment in turmoil, characterized by a lack of political commitment and policy inconsistencies. This bleak future is a warning of the potential repercussions of political upheavals and the failure of governance on the crucial water-energy-food nexus. The scenario emphasizes the importance of responsible and committed governance for a sustainable and equitable future.

Scenario 4 (characterized by business-as-usual management of the WEF nexus): "The Stagnant Nexus of 2050" or "Unchecked Trajectory – Depletion of the Water-Energy-Food Nexus by 2050"

In 2050, the country finds itself locked in a future marked by the consequences of a business as usual (BAU) approach to the water-energy-food nexus. This future, moulded by imperfect management and unsustainable practices, presents a stark warning of the dangers of inertia.

Agriculture – Agriculture faces severe challenges, with declining outputs and a lack of support. Food security is no longer a guarantee, and a significant number of communities, particularly in rural and underprivileged areas, struggle to obtain enough food for their basic needs.

Municipalities – Municipalities are characterized by low levels of services and budget losses, leading to frequent protests over increased demands. Pollution escalates unchecked, driven by a lack of enforcement and political instability.

Industry – The industrial sector suffers from a scarcity of food and resources, combined with a lack of support. Conflicting legislations and lack of implementation hinder industry's ability to adapt and innovate. Consequently, the sector struggles to keep up with global competition and fails to provide adequate employment opportunities.

Environment – Environmental degradation accelerates as the awareness and respect for biodiversity declines. Ecosystems in the catchment collapse under the pressures of overuse, pollution, and climate change, threatening not only the planet's biodiversity but also the essential ecosystem services upon which all life depends.

Water – Water resources are under tremendous stress in municipalities but also throughout the WMA and the country at large. The increase in population and industry, combined with climate change, escalates the demand for water. Conflicts over water become increasingly common in the catchment, with poor management exacerbating the situation.

Conservation and demand management practices are neglected, leading to inefficient water use. Pollution increases, further reducing the availability of clean water. Restrictions on water usage become common, but they are frequently flouted due to the dysfunctional local municipality structure.

In certain regions, tensions over water resources escalate into full-blown water wars, further destabilizing the geopolitical landscape. The crisis reaches a point where unsustainable livelihoods become the norm, with entire communities struggling to secure access to basic needs.

The year 2050 stands as a grim testament to the consequences of a BAU approach to the management of the water-energy-food nexus. This future scenario underscores the importance of proactive, sustainable management practices to ensure that the catchment's resources are preserved for future generations.

7.3.3 Sector-specific visions

As a separate activity, participants were then divided into their sectoral groups and asked to create sector-specific visions up to 2050. The five visions that were created are shown in Fig. 7.9.

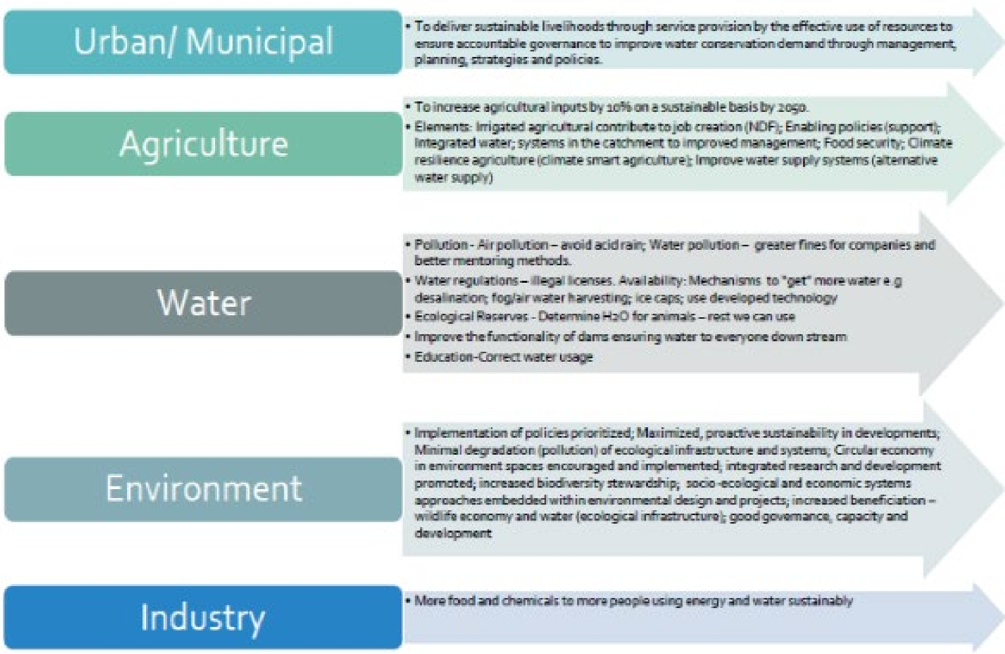


Figure 7.9 Sector-specific visions developed in the PSD process.

Participants emphasized principles of good environmental governance across all sectors as well as effective policy implementation, proper maintenance of infrastructure, the sustainable use of water, and the importance of improved awareness of environmental sustainability by various stakeholders. Interestingly, participants also placed an emphasis on the use of technology and innovation in achieving various sectoral visions (e.g. implementation of climate-smart agriculture) and identifying alternative water sources (e.g. desalination).

7.3.4 Integrating sector-specific visions into scenarios

After the sector-specific visions were developed, a member from each sectoral group was asked to join a scenario group. Sectoral group representatives were then tasked with bringing into the scenario group discussion the discussion points from the sectoral groups as well as the sectoral visions. Collectively, the scenario group, made up of sectoral group representatives, was then asked to co-develop the scenario and discuss its impact on the sectoral visions.

A few key elements are worth noting. Under the climate change scenario (hotter, drier, more floods), sectoral visions could still be achieved if adaptation strategies were put in place, i.e. the pathways to achieve the sectoral visions might be different. Under a climate change scenario, there is a greater risk of disease outbreaks, and a greater risk of damage to infrastructure. This implies that the social and economic impact on individuals, institutions and industry will be great if robust adaptive measures are not implemented. Under the socio-economic change scenario, international environmental standards as well as industry standards are a growing challenge for importing industries. Similarly, adherence to environmental management compliance was also seen as an important factor for water allocation plans to be effective. Finally, the power of partnerships, particularly public-private collaboration and support (e.g. government subsidies) was seen as a critical factor in ensuring the agricultural sector remains competitive. The political/policy change scenario had a broader conceptualization but saw a situation depicted by self-interested politicians exerting power in the administrative sphere, and less transparency in governance procedures. The BAU scenario saw a similarly bleak future depicted by unsustainable livelihoods with continued declining trends of reduced food security, lower levels of service delivery, further budgetary constraints, further environmental degradation and increased stress on water resources with more conflicting demands.

7.3.5 Discussion and analysis of PSD output: Adaptation options

In terms of the design, some participants struggled with the approach of developing a sector-specific vision and then integrating it into a WEF nexus vision. When groups had to identify adaptation options for each WEF nexus vision, common areas included the following:

Agriculture:

- The need to pilot and scale climate-smart crops (yellow and white maize in drylands, hydroponics).
- There was a sense that if emerging farmers were equipped with improved knowledge, they would be more resilient to climate change.

Municipal:

- There was a strong articulation of the need for mentorship, knowledge sharing, and skills development in multiple sectors.
- Cooperative governance in the municipality and across sectors and institutions needs to be improved, with an improved model and clear separation of duty between political organizations and administrative governance at the municipal level.
- Several participants emphasized that the municipality needs to reduce temporary posts and avoid high staff turnover. The municipality should also reduce the use of service providers and put greater emphasis on job creation.
- Participants articulated the need for conservation/environmental education and awareness in municipalities.
- The municipality should invest in dry sanitation and accelerate water conservation and demand management efforts (e.g. 'war on leaks').
- Participants also felt that the interference by politicians/individuals should be reduced, particularly in tender processes. Good programmes should be de-politicized.

Environment:

- Focus on policy implementation and increased environmental awareness.
- Crackdown on illegal trading.
- Provide incentives to stimulate eco-tourism growth.

Water:

- The catchment should prioritize more infrastructural development, particularly dams, and better maintenance.
- The catchment should implement the research study recommendations.

A wide range of issue areas emerged that shape decision-making and prioritization of stakeholders in the WMA. These include but are not limited to political interference in municipal and administrative functions, global competitiveness on agriculture, low maintenance of infrastructure and other resource limitations, as well as limited capacity and awareness. These drivers are consistent with those outlined in existing literature: competition, authority, information on the costs and benefits of alternative production mechanisms for public goods, externalities, transaction costs, and access to financial, human and natural resources.

7.4 FOCUS GROUP DISCUSSIONS

The third qualitative research method used to triangulate the interview and PSD results was focus group discussions (FGDs) (Appendix 1.2). In terms of the two FGDs conducted, several themes and sub-themes emerged with the stakeholders from the IUCMA and Mbombela LM. The information below is extracted directly from the FGD transcripts. Quotes have been inserted where a FGD participant said something particularly poignant. Of the two FGDs conducted, one involved a management group of eight IUCMA individuals around the various decisions structures involved in the distribution and/or development of WEF nexus policies. Participants included senior staff from the water resource management unit, licensing, water quality and staff from stakeholder engagement and coordination units. The second FGD was held with officials from Mbombela LM, from the Environmental Management and Planning Department.

7.4.1 Data processing of FGD information

See methodology in section 5.3.

7.4.2 FGD analysis

The FGD methodology is mainly an interactive exercise allowing participants to share their perceptions on factors influencing their decision-making (within their organization and as individuals), providing a definition of the WEF nexus and how it influences their day-to-day decision-making, planning, design and implementation. Lastly, a detailed discussion was held on the existing policies and data sources used that apply to an integrated WEF nexus lens or approach in participants' jobs or scope of work.

Factors influencing the decision-making process

From the analysis, several factors that influence decision-making in policy planning processes were identified: stakeholder consultation or engagement; strategic priorities; politics; budgetary constraints or availability; and institutional mandates. Stakeholder engagements came out strongly as one key factor influencing decision-making processes and policy implementation. This gives a platform for stakeholders to articulate the challenges that are faced by the community and possible tailor-made solutions for those challenges. Stakeholder engagement in policy formulation and decision-making builds trust and mutual understanding between policy-makers and relevant stakeholders. In addition, strategic policy priorities, as outlined in higher level policies, were also listed as a key driver of the policy-making and planning processes at the catchment level. Interestingly, participants also mentioned the use of indigenous knowledge, which is often ignored in policy development as a source of primary data in decision-making. There was an urge to build evidence- and knowledge-based research and decision-making that will engage and incorporate both indigenous knowledge and science in a more comprehensive and meaningful way, especially for environmental change.

In both the IUCMA and Mbombela LM FGDs, stakeholder consultation and/or engagement was highlighted having an important influence on decision-making and planning processes. This seems logical on a practical level as stakeholders may articulate the challenges that are faced by the community also bringing ideas of solutions for those challenges. This will build trust and mutual understanding between policy-makers and stakeholders. Furthermore, what emanated from both group discussions as a factor that influences the decision-making process is resource allocation. The participants elaborated that most of the time budget constraints influence decision-making and sometimes projects are not implemented due to lack of funds. The IUCMA emphasized that strategic priorities as set by the Department of Water and Sanitation (DWS) influence their decision-making processes (Fig. 7.10 & 7.11). This is in keeping with the principle of subsidiarity. Hence, for them, it is crucial to have a good working relationship with DWS. Lastly, the Mbombela LM group explained the political interest and influence on the decision-making (Fig. 7.12). One participant mentioned: "…for the project to be implemented, successfully and sustainably, one has to do what is needed by politicians who have an interest in the project, they tend to influence the direction of the project".

Figure 7.10 Main factors influencing decision-making processes and planning in participants' jobs as shown by the frequency of words used in the focus group discussions (FGDs).

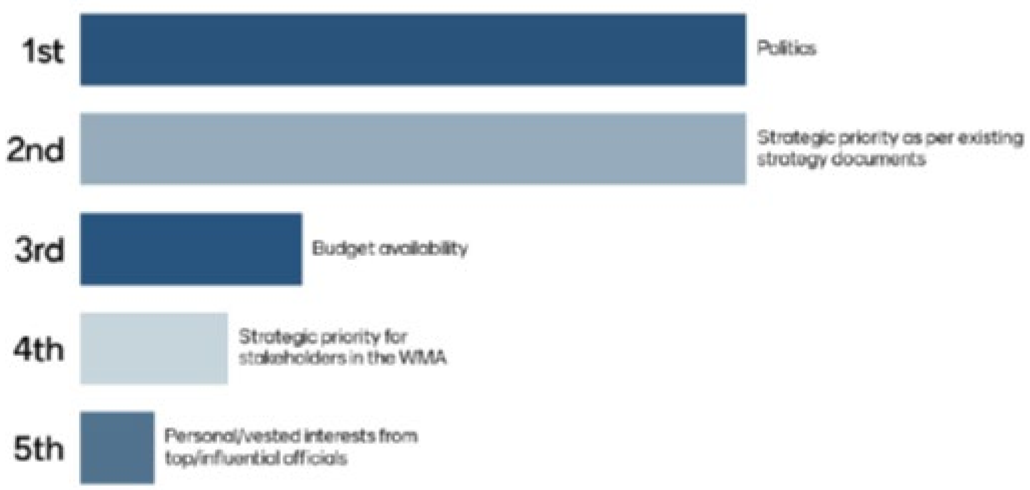


Figure 7.11 Main factors influencing decision-making processes and planning in participants' jobs in order of priority.

Factors influencing policy implementation

The issues of budget constraints and political influence emanated again as factors hindering policy implementation in both the IUCMA and Mbombela LM. The involvement of community members was highlighted as a hindrance to policy implementation. This happens as some projects are not a priority for communities, yet the municipality may see them as necessary (e.g. clean quality air). On the same note of community involvement, respondents expressed that community members sometimes want to be involved in projects even though they lack the expertise to implement them, driven by a lack of job opportunities in rural areas. Eventually this can result in project implementation being blocked by community members, if the municipality does not comply with their demands. This shows that stakeholder involvement is an integral part of decision-making and may involve continuous information sharing, consulting, dialogue or deliberating on decisions.

Figure 7.12 Main factors influencing policy implementation in participants' jobs from frequency of words used in the FGDs.

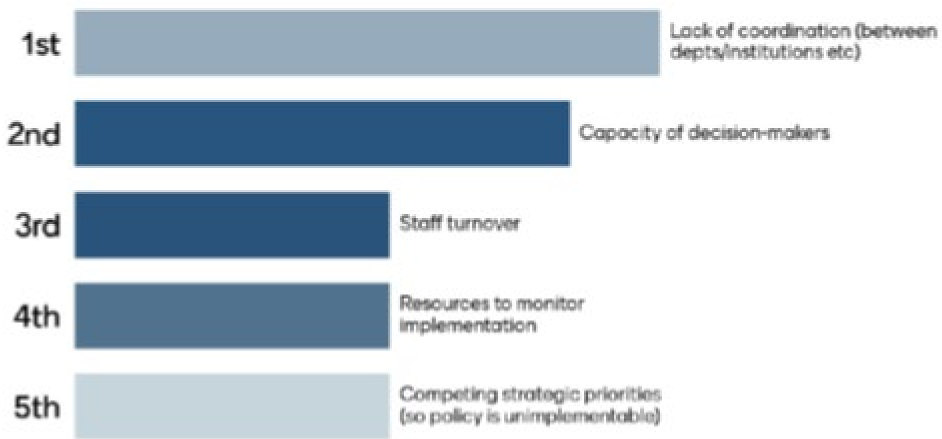


Figure 7.13 Main priorities influencing policy implementation in participants' jobs.

How the WEF nexus supports day-to-day decision-making and planning

The WEF nexus forces institutions to be innovative, adapt to difficulties, and perform strategic priorities as expected in the presence of constraints. According to the Mbombela LM group, the WEF nexus allows projects to be included in the Integrated Development Plan (IDP). This means that there is allocation of project budget and project managers must report on progress and the impact of the project. When projects are not prioritized they are excluded from the IDP and thus become an unfunded mandate. The WEF nexus allows stakeholders to be engaged from different fronts in the policy development process and give inputs when developing tailored solutions for the communities. This is crucial in policy development as stakeholder input increases the quality and trustworthiness of policies aimed at improving the quality of life and success in achieving the outcomes.

Data sources informing decision-making

The focus groups revealed that they rely on data from secondary sources although they seldom collect such data to inform decision-making. This is because the primary data collection process is expensive for a rural municipality that is underfunded. It is also time-consuming and they have insufficient capacity to do a fully-fledged survey whenever they must implement a project. The Mbombela LM group mentioned that most of the time they adapt other plans, such as strategies that have been implemented by the metros, and align them with their own municipality needs in a rural setting. One participant said: “We adopt strategies already implemented by metros in the country as they are ahead on the plans and have done extensive research on the feasibility of plans or strategies before they even implement them”.

The most interesting point that came out from the discussion is the use of indigenous knowledge, which is often ignored in policy development. There is an urge to collect evidence and perform knowledge-based research and decision-making that will engage and incorporate both indigenous knowledge and science in a more comprehensive and meaningful way, especially to address environmental change. Lastly, stakeholder consultation came out strongly during the discussion as a source of local information and data to be used for decision-making. This shows that stakeholder consultation is crucial when considering the WEF nexus to enable collaborative and co-production of useful knowledge and services for decision-making.

Policies/strategies that apply daily in the workplace

The IUCMA have an intergovernmental stakeholder engagement strategy developed internally to provide direction on how to engage stakeholders from numerous government departments (local and national) as well as stakeholders that are not directly in the water sector but affected by decisions that are made by the water sector. This strategy is still to be approved by the IUCMA board. Another common instrument that is used by the IUCMA is the ‘interim transboundary flow requirement’ that emulates from an agreement or a treaty between two or more countries – in this case South Africa, Eswatini and Mozambique – based on a volumetric water allocation and certain quality requirements (TPTC, 2002). The current treaty is between Mozambique and Eswatini and both countries have access to the water data at the boundary entry point of the countries.

7.5 SCIENCE COMMUNICATION ABOUT WEF NEXUS

It is vital to be able to communicate our scientific concepts and findings to the general public. Therefore, one needs to make an effort to formulate the scientifically correct messages in simple everyday language with as little jargon as possible. This is particularly important for the concepts of the WEF nexus as water is vital to all forms of life and can often result in unpleasant conflicts between people and organizations. However, the ideas are not always so easy to explain and convey to rural people, so a survey was conducted to establish what people know about science communication. Some innovative ways were developed to describe the concepts and deliver a clear message to the users in rural areas, especially where English is not their mother tongue. Two methods were used in this project to convey the messages of WEF nexus and how it would affect one’s everyday life, as well as to present the concept of the dilemma facing those responsible for the allocation and division of the limited amount of available water to users in the catchment. These two methods were the illustration of a bucket of water and a diagram showing the water users across the catchment with the main features.

7.5.1 Results from science communication questionnaire

A questionnaire was developed to investigate the local knowledge about science communication (Appendix 1.3). A total of 50 questionnaires were distributed and 48 were collected to give the information in Table 7.3. Those answering the survey were predominantly from the local agricultural and water sectors, as can be expected as the survey was carried out at the Catchment Management Forums. Mostly they had been involved in the data collection and development phases of this project. In general, they would like to have regular updates on the project via meetings or workshops, although there are time constraints and personal and financial limitations to further involvement.

Table 7.3 Results of survey about science communication, where multiple answers were possible in many questions (see Appendix 1.1 for survey questionnaire)

Question	Possible Answers							
1	Agric	Energy	Water	Media	Policy	Science	Business / Industry	Other
	29	4	20	0	1	3	3	2
2	Local	National	Regional	International				
	37	5	12	3				
3	Yes	No						
	16	29						
4	Development	Data collection	Data analysis	Interpretation of results	Dissemination of results	Other		
	16	20	2	3	3	1		
5	Regular updates	Meetings	Regular workshops	Digital / visual tools	Personal dialogues	Participate in field work		
	21	19	14	7	4	11		
6	Time constraints	Personal limitations	Financial limitations	Organisational limitations				
	23	17	18	9				
7	Yes	No						
	36	13						
8	Yes	No						
	40	3						

7.5.2 Use of posters to communicate WEF nexus scientific concept

A number of visuals were developed to communicate the concepts of the WEF nexus to those at grassroots level. These were particularly used during explanations at the Water Management Forums.

7.5.2.1 Water allocation bucket diagram exercise

In order to describe the concepts addressed by the WEF nexus, such as water allocation, an image of a set amount of water that the general public can understand was used. A diagram of a bucket containing 10 litres of water (Fig. 7.14) was used to help participants to visualize a finite amount of water that must be divided among the users. At the Crocodile and Sabie-Sand forum meetings, participants were requested to allocate this water to three different sectors: agriculture, energy and domestic use. The results show that the participants favoured the agricultural sector by allocating it between 36-43% of the available water, followed by 30-34% allocated to domestic use, with the lowest amount allocated to energy production at 26-28% (Fig. 7.15). This division of water is expected as the participants in both catchments are predominately rural inhabitants relying heavily on farming.

The WEF nexus bucket diagram proved to be a useful tool to understand how stakeholders allocate resources in a catchment area such as the Crocodile and Sabie-Sand. It shows that the people understand the interconnections between water, energy and food as the diagram provided a visual representation of how these resources can be allocated among different sectors. In this case, the findings of the WEF nexus water allocation exercise showed that the highest amount of water resources in the Crocodile and Sabie-Sand catchments were allocated to agriculture (39.8%) and about a third to domestic use (32.6%). Meanwhile, only 27.6% of the water resources were allocated to energy production by the participants.

The high allocation of water to agriculture in the Crocodile River Catchment indicates that agriculture is considered as a priority by stakeholders in that area. Agriculture is a critical sector in many developing countries, including South Africa, as it provides food, fibre and income to many people. As a result, it is not surprising that water resources were allocated to agriculture to support its growth and development.

The second highest allocation of water to domestic use in the Crocodile River Catchment indicates that household water security is also a priority for the local population. Domestic water use is essential for human health and well-being, and ensuring that water is available for this purpose is a critical aspect of water resources management. The fact that water resources have been allocated to domestic use may also reflect the importance of water for other household and community uses, such as hygiene and sanitation.

The lower allocation of water to energy production in the Crocodile and Sabie-Sand catchments may indicate that energy generation does not rank as a high priority by stakeholders in the area. Energy production requires large amounts of water, and in some cases, the water used in energy production is not available for other uses. However, as the energy generation plants are not located in either of these areas, it may be a case of lack of awareness of the need for water for this purpose.

It is important to note that these allocations of water resources may not be optimal, and there may be trade-offs between different uses. For example, allocating more water to agriculture may lead to less water being available for domestic use, and vice versa. Similarly, allocating more water to energy production may lead to less water being available for agriculture and domestic use. This is why water governance is critical in maintaining the balance.

In conclusion, the findings of the WEF nexus diagram exercise in these two catchments provided insight into how stakeholders perceive and value different uses of water. The high allocation of water to agriculture and domestic use may indicate that these sectors are seen as priorities, while the lower allocation of water to energy production may indicate that energy is not seen as a priority. These findings highlight the importance of considering the interconnections between water, energy and food when allocating resources in a catchment area. It is crucial to ensure that water resources are allocated in a sustainable and equitable manner to support the development and well-being of all stakeholders in the Inkomati-Usuthu Water Management Area. This exercise also served a useful educational purpose and as part of an awareness campaign amongst the participants to help them to understand the pressures on the water resources and the decisions that the CMA needs to make.

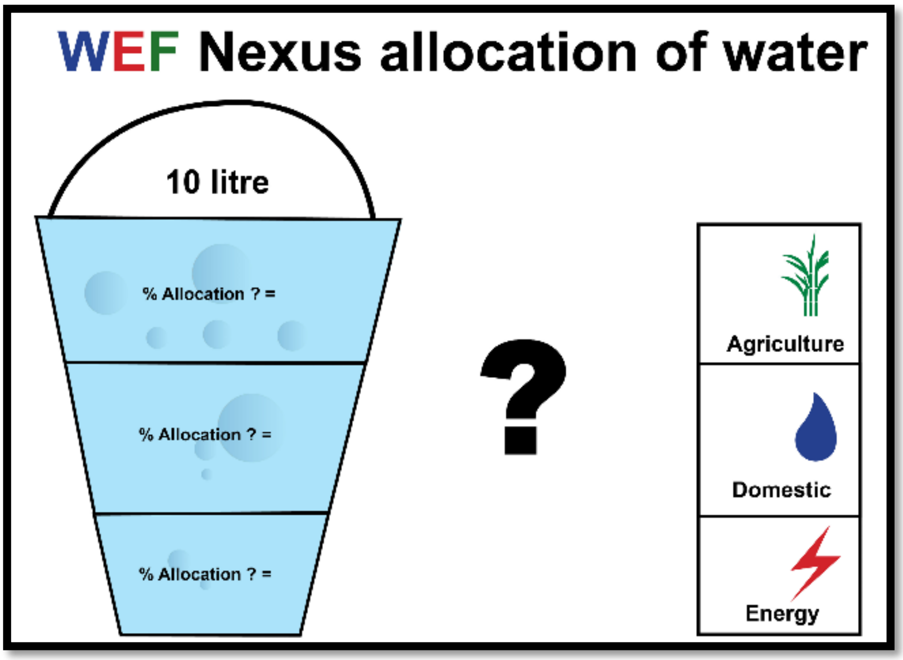


Figure 7.14 Diagram showing water allocation bucket of 10 litres to be divided amongst the three sectors – agriculture, energy and domestic use.

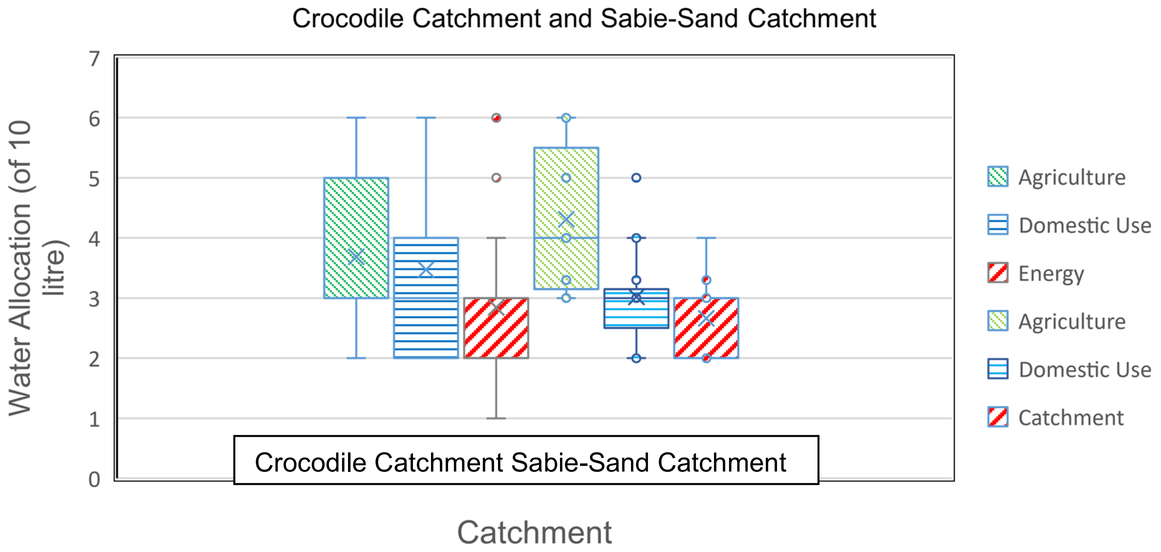


Figure 7.15 Water allocation according to participants at the Crocodile and Sabie-Sand Catchment Forum meetings.

7.5.2.2 WEF nexus diagram of the Crocodile River Catchment

A diagrammatic representation of the WEF nexus in the Crocodile River Catchment was presented at the forum meetings. The presentation was centred around the diagram developed to help the participants visualize the interconnections between the different components of the WEF nexus (Fig. 7.16). This diagram shows the flow of water resources within the Crocodile River Catchment, highlighting the key factors that influence the sustainable use of water, energy and food resources. The key elements are illustrated, namely sugarcane fields and sugar mill, power station for energy generation, and communities as well as the IUCMA and the Crocodile Irrigation Board as the water allocation agencies. The WEF nexus diagram is a tool that provides a visual representation of the interconnections and interdependencies between the water, energy and food systems. The diagram highlights the interlinkages and trade-offs between the three sectors and helps stakeholders to understand the complex and dynamic relationships between them.

The participants at the forums had a positive reaction to this diagram and were able to grasp the concept of the WEF nexus quickly. They showed a good understanding of how the components of the nexus were interconnected and how they impacted each other. The participants were able to identify the different challenges faced in this catchment, such as water scarcity, energy insecurity and food insecurity, and how these challenges could be addressed through sustainable practices. The feedback from the participants was overwhelmingly positive, and they praised the clarity of the diagram and the ease with which it helped them understand the WEF nexus. Some participants even stated that they would be using this diagram in their own work to help explain the concept of the WEF nexus to others. The success of these presentations is a testament to the power of visual aids in communicating complex concepts. Using this diagram to help the participants understand the WEF nexus was an opportunity to provide them with a clear and concise understanding of the interconnections between water, energy and food resources and the challenges that faced the catchments. This has the potential to inspire positive change and encourage the adoption of sustainable practices, ultimately leading to a more resilient and sustainable future for the Crocodile River Catchment.

The positive feedback from the participants highlights the importance of using visual aids in communicating complex concepts and the role that they can play in promoting sustainable development. By presenting the WEF nexus in a clear and concise manner, researchers were able to help the participants understand the interconnections between water, energy and food resources and the challenges that are faced in the Crocodile River Catchment. This has the potential to inspire positive change and encourage the adoption of sustainable practices, ultimately leading to a more resilient and sustainable future for the catchment.

In the context of the Crocodile River Catchment, the WEF nexus diagram (Fig. 7.16) is a valuable tool that can assist stakeholders in making informed decisions about the management and use of the catchment's water resources. The diagram provides a comprehensive view of the water, energy and food systems in the catchment, including their sources, uses and interdependencies. For example, the diagram can help stakeholders to understand how water is used for irrigation in food production, hydroelectric and coal-fired power stations for energy generation, and municipal supply for domestic use, and how these uses impact the availability of water for other uses such as food production. Similarly, the diagram shows how energy demand affects water usage and how food production depends on both water and energy resources. The WEF nexus diagram also helps to identify opportunities for improving the sustainability of the catchment's resources, by highlighting areas where more efficient and integrated resource management can be addressed to reduce waste, conserve resources, and support economic development. For instance, the diagram highlights areas where water can be conserved through more efficient irrigation practices, or where energy can be generated from renewable sources, reducing the dependence on fossil fuels.

In conclusion, the WEF nexus diagram of the Crocodile River Catchment is a valuable tool for stakeholders who want to understand the interconnections and interdependencies between the water, energy and food systems. By providing a comprehensive view of the use of the catchment's water resources, the diagram can help stakeholders to make informed decisions about resource management and use, and support the development of more sustainable and integrated resource management practices.

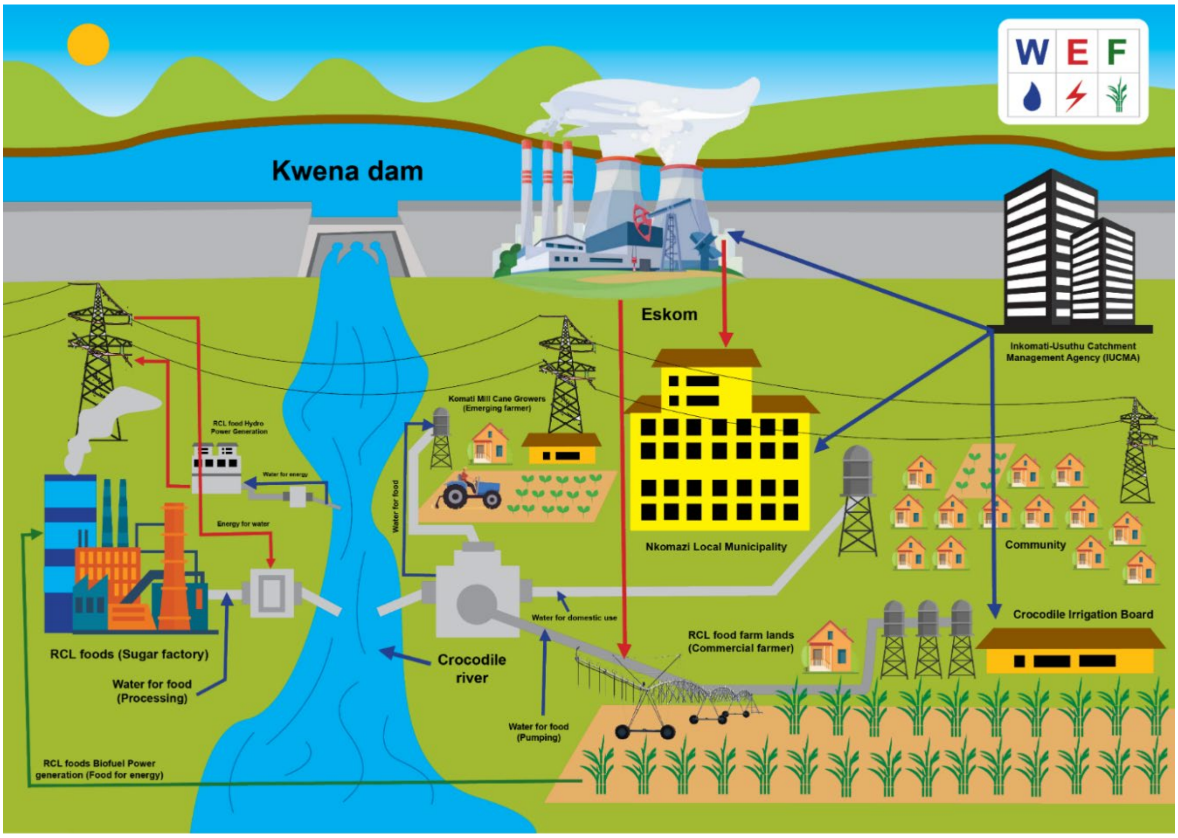


Figure 7.16 Diagrammatic representation of the WEF nexus in the Crocodile River Catchment (Machimana, 2023).

7.6 CONCLUSION

The results from the first round of semi-structured interviews and FGDs have provided much useful information from the stakeholders about the WEF governance in the Inkomati-Usuthu Catchment. This provides a basis to begin to understand how the various organizations interact and operate concerning matters of water policies, and implementation of water use and water allocations. One thing is clear though – participatory stakeholder engagement in WEF nexus decision-making is key. But while engagement processes are considered important in this catchment, feedback loops and processes of community validation of information gathered in participatory processes are lacking. A critical view of this would point to 'stakeholder engagement by stapling', i.e. a paper exercise to demonstrate stakeholder engagement but not for it to be truly considered and internalized in decision-making processes. This needs to be verified in follow-up qualitative research.

Context-specific practical and policy implementation guidance in evaluation and planning still needs to be improved. Budgetary constraints and human resource capacity limitations are some of the challenges faced by government stakeholders in ensuring this coordination of sectors is meaningful. It is suggested that ideally, locally-based WEF management should help ensure that WEF resources are managed in a holistic and equitable way; however, there is currently very little coordination, even within sectors. It is also clear that while the WEF nexus is a concept that stakeholders know about, in order for it to have a meaningful impact on stakeholder decision-making and move decision-makers from conceptual thinking to 'doing', starting from the lowest level (i.e. moving from conceptual ideas to practical and relevant applications), sectoral coordination is key. This could be achieved through the means explained in the conceptual framework: coercion, competition or collaboration. At the same time, it is critical to prevent delays in the process of decision-making that can be caused by ineffectiveness of time allocation to accommodate the various kinds of stakeholder's interests.

Finally, four principles and perspectives for future WEF nexus framework development – namely to make them more understandable, to ensure reliable and valid data, to make them adaptable to many diverse situations, and to be applicable across scales – are considered central to increasing the benefits and improving the role of the WEF nexus concept in influencing policy and resource planning processes. Continuous improvements, especially in grounding the WEF nexus concept, indicate the urgent challenge to better manage the three resources of water, energy and food.

The science communication activities certainly helped those attending the Water Management Forums to gain a deeper insight into the various aspects that need to be addressed in water allocation decision-making. The concept of a limited amount of water being available was brought across clearly by using the 10 litre bucket idea. Participants then also had a feel for some of the interconnected aspects of which sectors are demanding water and what trade-offs need to be made to divide and fairly allocate the limited water supply.

As discussed in the WEF approaches above, the application of more WEF tools is needed at catchment level as the data is mostly only available at national scale. Therefore, looking at catchment scale can be limiting, as some of the data is rather old and not current. The application of the tools in other scales can give clearer scenarios than currently provided. The proposed output of the project will be guidelines concerning water demand allocations, particularly for the agricultural industry. This will assist the Inkomati-Usuthu Catchment Management Agency and other agricultural stakeholders in their decision-making and in policy formulation.

CHAPTER 8: APPLICATION OF WEF NEXUS TO INFORM RESOURCE UTILIZATION IN THE CROCODILE RIVER CATCHMENT

8.1 INTRODUCTION TO CASE STUDY FOR WATER RESOURCE MANAGEMENT DECISION-MAKING GUIDANCE USING A WEF NEXUS LENS

Water-Energy-Food (WEF) nexus thinking recognizes that resources are linked and that the use of one resource should not compromise another. In Mpumalanga Province, in which the Crocodile River Catchment is located, 25% of the staple food is produced on irrigated land, so water, energy and food are tightly linked (Simpson et al., 2019). Around 46% of South Africa's high potential arable soils are found in Mpumalanga (BFAP, 2012). There is long standing competition for land between the mining and agricultural sectors, and both have had negative impact on water quality in the region (Van der Laan et al., 2012).

In 2015, 91.4% of households had access to improved water sources but only 65.8% to improved sanitation facilities, while 16.5% of households experienced water pollution (StatsSA, 2016a&b; Simpson et al., 2019). Municipal water losses are very high in Mpumalanga, ranging between 33.6% and 51.3% (compared to an international best practice target of 15%) (McKenzie et al., 2012; Bruinette and Claasens, 2016). Households in Mpumalanga connected to the national electricity grid increased from 75.9% in 2002 to 89.8% in 2014 (StatsSA, 2015). However, 27.4% of households in Mpumalanga experienced either inadequate (8.4%) or severely inadequate (19%) access to food (StatsSA, 2015). Therefore, it is critical to assess the tradeoffs and compromises needed to allocate the scarce water resources.

There is water transfer from the Sabie River to the Crocodile River Catchment to support the Nsikazi North demand centre (DWS, 2021b). The largest user of water in the Crocodile (east) catchment is irrigation (467 million m^3 $annum^{-1}$) followed by commercial forestry (158 m^3 $annum^{-1}$) (DWS, 2021b). User water requirements in the Sabie and Crocodile catchments comprise irrigation (54%), afforestation (22%), urban-industrial (13%), invasive alien plants (6%) and the environment (5%). The Inkomati Tripartite Permanent Technical Committee (TPTC) has established that a minimum of 37 m^3 $annum^{-1}$ are required to flow from these catchments into Mozambique (TPTC, 2002). The ecological water requirements as stipulated by the National Water Act [Act 36 of 1998 (NWA)] have been determined and gazetted for the rivers in these catchments and range from 12.5 to 45.4%.

Groundwater is generally not available for large-scale extraction in the catchment, except in the areas of the Kaap and Lower Crocodile rivers, where there is potential but low domestic demand (DWS, 2021b; MuSSA, 2015).

8.2 METHODS USED IN CASE STUDY

It was decided to use the WEF nexus concepts and tools in a realistic case study by developing decision-making guidance for water resource management. Therefore, a WEF nexus lens was applied to the issue of water scarcity and increasing demand in the lower Crocodile River Catchment. The aim was to compare two plausible scenarios currently being considered by the IUCMA to address current and projected water shortages in the catchment by assessing the implications for the water, energy and food sectors. Such information could be used to inform decision-making and future strategic planning, and in policy formulation.

8.2.1 Candidate scenarios that were tested

a) 'Storyline A – Develop the resources': By building a new dam, most likely at Mountain View, that could provide an additional yield of 78 million m^3 yr^{-1} [Reconciliation Strategy (DWS, 2021a)].
b) 'Storyline B – Changing to crops with lower water requirements': Specifically switch from sugarcane to macadamias (sugarcane uses 15 000 to 17 000 m^3 ha^{-1} yr^{-1} and it is estimated that macadamia could use half of this volume of water).
c) 'Storyline C – Changing to a more efficient irrigation system': Specifically switch from a centre pivot to a drip irrigation system with an expected 5% increase in efficiency.

8.2.2 Switch to a more efficient irrigation system (centre pivot to drip irrigation)

The irrigation water allocations differ within the Crocodile River Catchment, with 13 000 m^3 ha^{-1} yr^{-1} allocated to the section above the gorge and 8 000 m^3 ha^{-1} yr^{-1} to the section below the gorge. Based on Jarmain et al. (2014), it was assumed that sugarcane under pivot irrigation receives 1 000 mm of irrigation water and achieves a sucrose yield of 14.7 t ha^{-1}. The efficiency of drip irrigation at 95% is reported to be higher than for centre pivot at 90% (SASRI, 2017). To achieve a net irrigation of 1 000 mm, gross irrigation application of 1 111 mm for pivot and 1 053 mm for drip irrigation was assumed. Drip irrigation is reported to create more labour opportunities, with 14.4 man days ha^{-1} yr^{-1} for drip compared to 1.44 man days ha^{-1} yr^{-1} for pivot (SASRI, 2017).

Commonly used metrics in WEF studies can be useful for comparisons within and across studies. In this study, water use efficiency (WUE, kg m^{-3}) is defined as utilizable yield harvested per unit of volume of water used:

$$Water\ use\ efficiency\ (kg\ m^{-3}) = \frac{Crop\ yield\ (kg\ ha^{-1})}{Water\ consumption\ (m^3\ ha^{-1})} \quad (1)$$

Energy productivity (kg MJ^{-1}) is defined as crop yield per unit of energy supplied:

$$Energy\ productivity\ (kg\ MJ^{-1}) = \frac{Crop\ yield\ (kg\ ha^{-1})}{Irrigation\ energy\ input\ (MJ\ ha^{-1})} \quad (2)$$

8.2.3 Switch to a more efficient irrigation system and change crops (sugarcane to macadamias)

Macadamia orchards are mainly grown in sub-tropical regions of the country, including the KwaZulu-Natal, Mpumalanga and Limpopo provinces. The trees can grow on a variety of well-drained soils. Measurements of macadamia water use are scarce. It is also noted that for the first 5 years the trees do not produce nuts and most likely use less water than a mature orchard due to a still-developing leaf canopy. Gush and Taylor (2014) reported the water use of a macadamia orchard planted with the Beaumont cultivar (*M. integrifolia* x *M. tetraphylla* hybrid) in White River, Mpumalanga. For the 2011/12 season, total crop evapotranspiration (ET) was estimated to be 809 mm (T = 478 mm, E = 331 mm), the rainfall received was 887 mm and the amount of irrigation applied was 335 mm. This value was assumed to be the irrigation applied to macadamias in this study. The South African Macadamia Association (SAMAC) reports that 510 litres of water are needed to produce 1 kg macadamia nuts, and it has also been reported that 1000 litres of water are needed to produce 850 g of nuts (https://themacadamia.co.za/2018/10/23/do-we-have-enough-water-for-all-our-macs/, accessed 27 April 2023). Water productivity can be expected to change according to environmental conditions and tree age, as well as culitvar.

Following harvest, macadamia nuts need to undergo de-husking followed by removal of the inner-shell to obtain the edible kernel. The quality of the nut is a stronger driver of market price. Poorer quality nuts are processed into oil. The shells can be used for other purposes, such as being burnt to make carbon filters, applied as a garden mulch, to provide energy for macadamia dryers, in the manufacture of plastic, and as a replacement for sand in the sand-blasting process. In addition, oils extracted from culled nuts can be used as inputs for soaps, sunscreens and shampoos (DAFF, 2012; Genis, 2020).

It was estimated that in South Africa in 2017, the macadamia nut industry created 7750 permanent jobs and an additional 8150 jobs during peak season (https://valleymacs.co.za/2018/12/10/the-economic-value-of-macadamia-farming-in-sa/). The subtropical fruit industry has been estimated to create work for two labourers per hectare and around 1.3 jobs per hectare in upstream and downstream linkages (Sibulali, 2018). Sibulali (2021) estimated that 0.53 workers per hectare are required in the South African macadamia industry. SAMAC (2021) estimated that a full-time job for one worker per hectare is created. In 2020 the industry was estimated to employ 12 619 permanent and 11 111 seasonal workers on-farm (https://themacadamia.co.za/2020/11/13/macadamias-offer-employment-hope/, accessed 26 April 2023). The number of jobs created per hectare may vary depending on factors such as the size of the orchard, the level of mechanization, and the farming practices employed by individual growers.

The South African sugar industry was estimated to create 85 000 direct and 350 000 indirect jobs (https://sasa.org.za/test/facts-and-figures/, accessed 26 April 2023). If we consider that 85 000 jobs are created per 1 862 666 t sucrose produced, this equates to 0.05 jobs t sucrose^{-1}, and for 14.7 t ha^{-1}, this equates to 0.67 jobs ha^{-1}. An additional 2.76 jobs ha^{-1} are created indirectly using the same calculation method.

The value of macadamia exports in 2017 was estimated at R3.3 billion (in contast to R1.85 million for avocadoes and R320 million for mangoes) (Genis, 2020). Sibulali (2021) estimated that exports grew from R105 million in 2007 to R4.6 billion in 2019. Over 95% of South Africa's macadamia crop is reported to be exported either as nuts in shell or kernels, so it is dependent on the international price.

According to SAMAC (undated), macadamias have a C footprint of 2.3 kg CO_2e kg^{-1} nuts produced, while irrigated sugarcane has been reported to have C footprint of 0.6 kg CO_2e kg^{-1} sucrose (Pryor et al., 2017).

8.2.4 Build the Mountain View Dam

The Department of Water and Sanitation (DWS) aims to extend the Water Resource Reconcilitation Strategy to cover the entire Crocodile (east) and Sabie sub-catchments (portions of supply catchment that were previously neglected). Therefore, the report on 'Water Requirements and Availability Reconcilitation Strategy for the Mbombela Muncipal Area' (DWAF, 2014) was updated with 'The Continuation of Water Requirements Availability Reconciliation Strategy for the Mbombela' (DWS, 2021a). Besides the increase in the geographical area covered, the latter update of the strategy was intended so that it could remain 'relevant, technically sound, economically viable, socially accepatable and sustainable'.

The proposal is to build the Mountain View Dam on the Kaap River (Fig. 8.1 & 8.2). The aim is to work with the existing Kwena Dam (on the Crocodile River near Lydenburg) to provide releases downstream for irrigators, environmental requirements and international obligations. It will also be used to supply Mbombela, thereby reducing pressure on the Kwena Dam (DWS, 2021a). The proposed yield of the dam will be 78.1 Mm^3 yr^{-1}. The Mountain View Dam is estimated to cost approximately R873 422 420 (August 2020 rates) and is reported that no additional infrastructure will be required downstream. It was recommended by DWS (2021a) for higher levels of investigation.

The Mountain View Dam is estimated to have a maximum height of 74 m and a spillway length of 120 m (DWS, 2021a). Further estimates are still needed in number of jobs that will be created in building the dam, and in future development of tourism opportunities.

Figure 8.1 Location of the proposed Mountain View Dam (taken from DWS, 2021a).

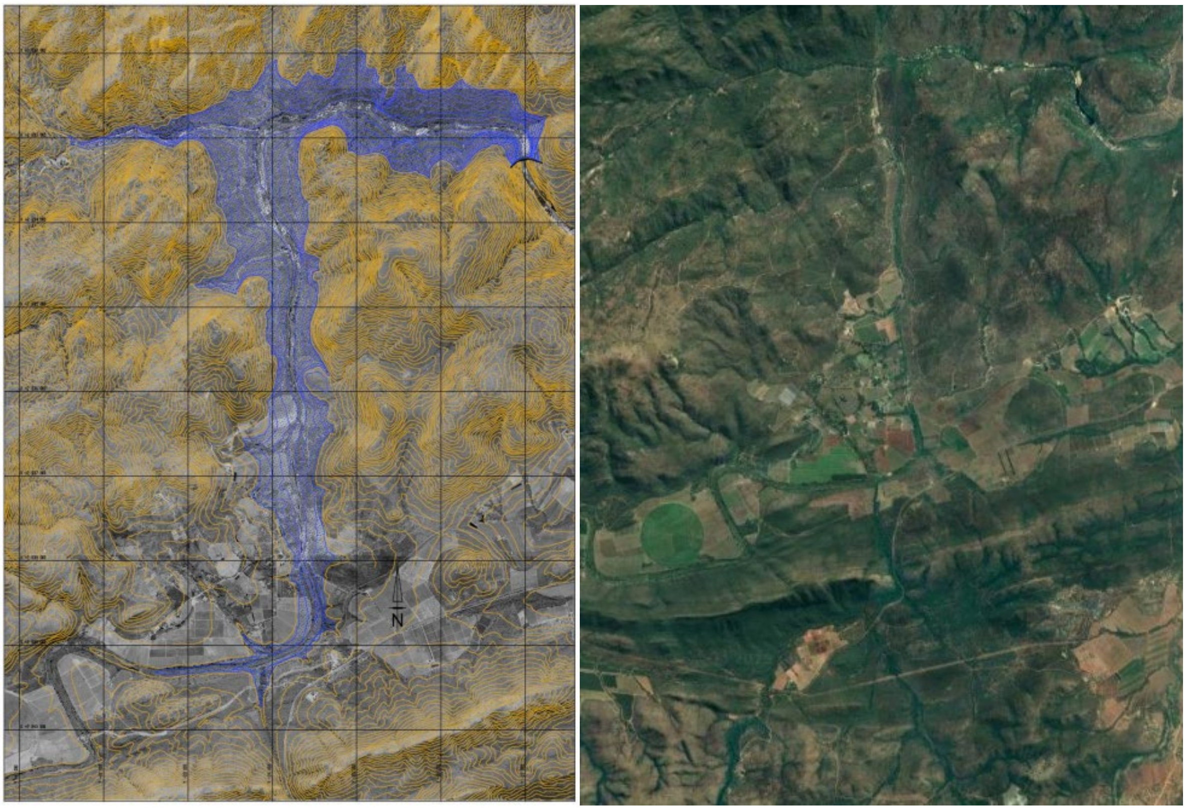


Figure 8.2 Plan for the proposed Mountain View Dam (left image from DWS, 2021a; right image from Google Earth).

The following assumptions regarding the proposed Mountain View Dam were made for this study:

- No hydroelectricity is produced from the dam.
- Due to the location of the dam, no agriculutural land was assumed to be lost as a result of building the dam.
- No loss of dam volume due to siltation was taken into account.

8.2.5 Calculation of WEF nexus indices

Sustainability polygons and integrated indices are commonly used in WEF nexus studies to compare alternative options or scenarios (Nhamo et al., 2020a). Each scenario was joined with lines to form polygons that represent potential benefits in terms of water, energy and food. Weighting indicators can further be assigned to balance value ranges and represent local priorities, which are subjective and attained through stakeholder consultation.

Nexus Webs is a framework that can represent different components and linkages in a river catchment, and add an environmental dimension to it (Leviston et al., 2018). The framework focuses on four main components: water use, assets, ecosystem services and well-being, each comprising several indicators. To enable comparison across different indicators and components, scores for each indicator are scaled between 0 and 1. The use of spider web plots facilitates the identification of interconnections across various sectors and goals, including trade-offs and synergies.

8.3 RESULTS OF CASE STUDY USING WEF NEXUS AS A DECISION-MAKING TOOL IN THE CROCODILE RIVER CATCHMENT

8.3.1 Switching to a more water-efficient irrigation system

Water

Based on the simple assumption that drip irrigation is 5% more efficient than pivot irrigation, a total of 133 504 ha would need to be converted from centre pivot to drip irrigation to achieve water savings equal in magnitude to the volume of the proposed Mountain View Dam. The 5% higher efficiency of drip over pivot assumed in this study can be considered a conservative number. Further water savings are possible since drip does not wet the canopy as pivot does which leads to underproductive evaporation of water. Utilization of drip irrigation could also enable the use of problem soil areas such as shallow or sandy soils with low water holding capacity where pivot may not be suitable.

In a global meta-analysis, Taguta et al. (2022) observed that switching from sprinkler to drip irrigation led to improved water productive use of +3.21 kg m^{-3}.

Energy

Converting land from sugarcane production under pivot to macadamia production under drip would require 536 kWh ha^{-1} $annum^{-1}$, resulting in an energy saving of 2168 kWh ha^{-1} yr^{-1}. This is similar to the estimate by Oosthuizen et al. (2005) for a drip irrigation system in the Onderberg region of Mpumalanga using 1 124 kWh ha^{-1} yr^{-1} to apply 718 mm. Due to South Africa's dependence on coal to produce electricity, lower electricity consumption would have long-term impacts on preventing agricutlural land being converted to coal mines, which in turn would have a less detrimental impact on water quality. In a global meta-analysis, Taguta et al. (2022) observed that changing from sprinkler to drip improved energy use by +4.4 tonnes MJ^{-1}. Energy producitivity is 1.5 kg sucrose MJ^{-1} for sugarcane under pivot irrigation, compared to 2.0 kg sucrose MJ^{-1} for sugarcane under drip irrigation.

Food

No change in the production of sucrose was estimated under this scenario as it compares sugar with sugar. However, drip irrigation is assumed to create more labour opportunities, therefore using only 1.44 man days ha^{-1} yr^{-1} for pivot and 14.4 man days ha^{-1} yr^{-1} for drip.

8.3.2 Switching to a more water-efficient crop

Water

Using the assumption that sugarcane requires 1 000 mm yr^{-1} while a macadamia orchard only requires 335 mm yr^{-1}, to achieve the same water savings to match the volume of the Mountain View Dam (78.1 Mm^3) would require the conversion of 11 744 ha of land from sugarcane to macadamia production. Assuming a development cost of R100 000 ha^{-1} (Van Wyk, 2018) for a macadamia orchard, the estimated cost is R1.174 billion. This does not include the cost of infrastructure to provide water to these new orchards, but some may be in place for sugarcane irrigation.

Energy

Converting 11 744 ha of land from sugarcane production under pivot to macadamia under drip could result in an energy saving of 2.55 GWh yr^{-1}, although this represents only 0.1% of the total electricity delivered to Mpumalanga Province in September 2016 (StatsSA, 2016b). Energy producitivity is 1.5, 2.0 and 3.1 kg MJ^{-1} for the sugarcane under pivot, sugarcane under drip, and macadamia under drip scenarios, respectively. A report on CO_2 emissions under the different storylines still needs to be compiled.

Food

Converting 11 744 ha from sugarcane to macadamias would reduce the sugar yield produced by 172 637 t yr^{-1} and increase macadamia nut-in-shell yield by 70 464 t yr^{-1}. High exports and foreign income can counter a deteriorating currency and assist the economy, potentially leading to indirect benefits to food security.

Manual as opposed to mechanical cracking of macadamia nut shells could fetch higher prices and create more employment opportunities, as is done in Vietnam (Botha, 2018).

South Africa is self-sufficient when it comes to cereal production, but while providing sufficient calories is important, often consumed as highly-processed, sugar-rich foods, it is often insufficient to meet people's nutritional requirements, leading to a condition called "hidden hunger" (Shackleton et al., 2008). This, in turn, can result in a rise in obesity and non-communicable diseases, as people consume more calories but do not receive all the necessary nutrients. Macadamia nuts are known to be highly nutritious with multiple health benefits since they contain mono-unsaturated fats, fibre, vitamins, minerals and antioxidants, and reduce calorie intake (https://www.globalafricanetwork.com/company-news/macadamia-nuts-the-future-of-high-value-crop-farming/). If more of the nuts can be consumed by locals it could improve food security, especially malnutrition, although it is recognized that the nuts are very expensive.

8.3.3 Building the Mountain View Dam

Water

An additional 78.1 Mm^3 would become available to the region and priority for the allocation of this water would be the city of Mbombela. Mpumalanga Province has a population of about 4.7 million people (https://www.gov.za/about-sa/south-africas-provinces, accessed 5 May 2023). The population falling within the Mbombela Local Muncipality was estimated to be 658 604 in 2011 and 695 913 in 2016 (https://municipalities.co.za/demographic/1244/city-of-mbombela-local-municipality, accessed 5 May 2023). If we assume a very basic human water requirement of 25 litres $person^{-1}$ day^{-1}, as incorporated in the reserve determination (DWA, 2013a&b), the city needs around 6.4 Mm^3 yr^{-1} for domestic consumption at an absolute minimum. Jackson (2014) indicated a region-specific volume of 198 m^3 capita yr^{-1} , which translates into a domestic water requirement of 138 Mm^3 yr^{-1} for Mbombela.

The Kaap River water has been reported to be of poor quality largely since it drains an area of active and closed gold mines (Van der Laan et al., 2012). If the decision to build a dam is taken, it should be done together with a regional land use and mine closure strategy (Simpson et al., 2019) so as not to be faced by major water quality challenges in the future. The high municipal water losses would also need to be addressed to fully utilize this water, which would result in energy savings from needing to treat less water to potable standards.

Energy

Since no hydroelectricity was assumed to be generated from the dam, no direct benefit in terms of energy was predicted. It was, furthermore, estimated that the dam would potentially lead to higher electricity consumption in the region due to increaed water availability to different users. Good quality water is, however, required in coal-fired power generation.

Food

If the current allocation of 54% to irrigation is applied to the new water made available from the Mountain View Dam, this could result in 42 Mm^3 of additional water for irrigation. This would enable, for example, the addition of 3780 ha of sugarcane under pivot irrigation or 11 912 ha of macadamias under drip. Optimistically this could result in an increased sucrose production of 55 567 t sucrose yr^{-1} or an additional 71 469 t macadamia (nut-in-shell) yr^{-1}.

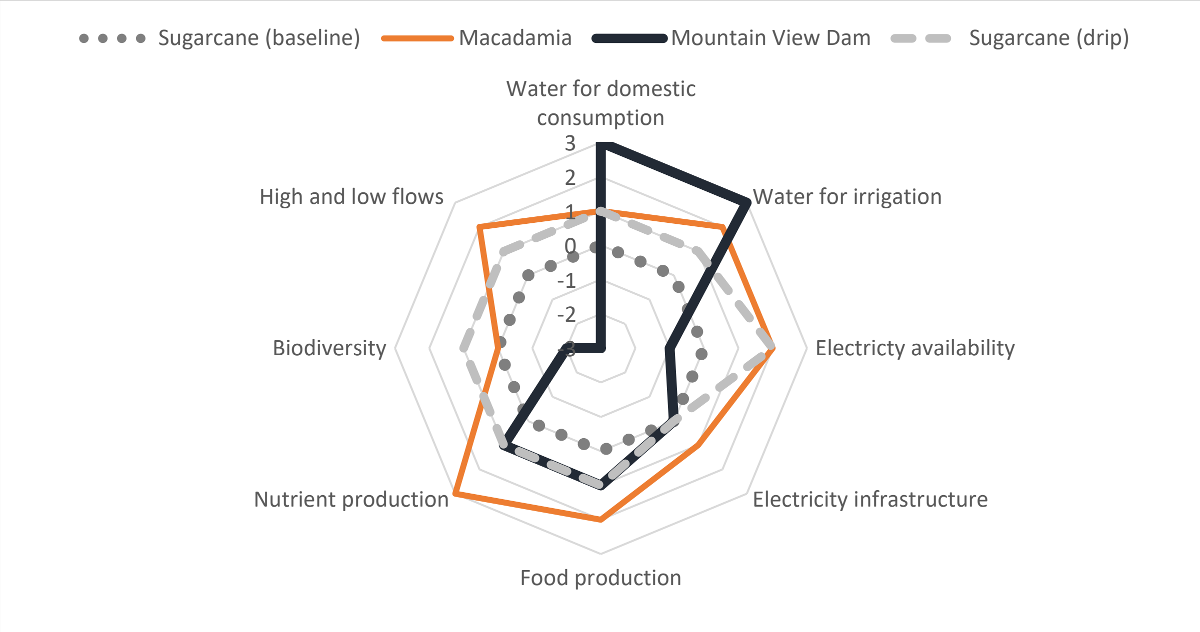


Figure 8.3 Spider diagram showing the comparison between the three different storylines using the WEF nexus indices to improve the water resources in the Crocodile River Catchment.

8.4 DISCUSSION OF THE DIFFERENT SCENARIOS

Switching to a more efficient irrigation system requires not only modernization of infrastructure and equipment, but also increased skills to manage the system. Even the best hardware that is managed poorly can lead to highly inefficient irrigation. While the capital costs of sprinkler systems are cheaper than pivot or drip, scarcity of water and electricity will lead to more efficient systems paying off in the longer term. While switching to 11 000 ha of more efficient irrigation systems will make only a very small impact in terms of increased electricity availability, all industries must take steps in this direction to have a meaningful impact. Solar and wind power systems that can be established remotely could benefit rural infrastructure needs. Solar powered irrigation pumps will likely have a bright future.

Investment of USD 8 billion in irrigated agriculture globally has failed to achieve the intended goals (Ringler, 2017) and many challenges are faced to create sustainable irrigation schemes, especially for small-scale farmers. Switching to a high-value tree crop like macadamia is expensive and requires a long-term view. Commercial growers consider 10-50 ha the minimum to make a profit, so large tracts of land with access to infrastructure including electricity, water, packhouses and good roads will be required (Genis, 2020). The trees can take 5 or more years to bear fruit and around 10 years before maximum yield, although initially other crops such as vegetables can be planted between the young trees to keep the land productive. Mature trees can then produce for up to 40 years. Due to the modernization and intensive post-harvest processing required, macadamia may not be an ideal crop for small-scale farmers without an adequate support network. Van Leynseele and Olofsson (2023) noted that expansion of the industry in South Africa over recent years has been driven by white commercial farmers, agribusinesses and to a lesser extent commercially-operated land reform projects.

Since macadamia nuts are largely an exported commodity, the industry should be positioned to extend its socio-economic contribution to the South African economy (Sibulali, 2021). There are concerns that the rapid growth of the macadamia industry in South Africa will not be sustainable and the 'bubble will burst', with China, among others, planting trees at a rapid rate (Parshotam, 2018). China is a major importer of South African nuts so the price will be dependent on their supply. For macadamia growers, theft is a problem, with at least 2000 t of nuts with a value of R146 million being stolen every year at various places along the supply chain (https://www.freshplaza.com/europe/article/2184404/south-african-macadamia-industry-satisfied-with-stiff-sentence-for-theft/, accessed 26 April 2023; Genis, 2020). Pests further threaten the viability of the industry in South Africa.

Being a C4 crop, sugarcane is not expected to benefit from the CO_2 fertilization effect under climate change as much as macadamia (a C3 crop). But water temperatures and more intense rainfall seasons may reduce the quality of macadamia nuts in South Africa (Bouarakia et al., 2023). Based on an increase in temperature in the region due to climate change, Gbetibouo and Hassan (2005) proposed that sugarcane farmers may to switch to more heat-tolerant crops such as sorghum. Irrigation of bioenergy crops could be a favourable solution for the region in terms of reduced energy requirement for water treatment and become a substitute for coal in the generation of electricity.

Dams can have a negative impact on the environment, including through the modification of aquatic ecosystems, the flow regime and migratory paths of birds. DALRRD already intends to develop 500 000 ha of additional land under irrigation (http://www.old.dalrrd.gov.za/Portals/0/Strategic%20Plan/Strategic%20Plan%202015%2016.pdf?timestamp=1683534085238, accessed 8 May 2023). Ideally this would be developed for previously disadvantaged groups, but large-scale producers are better able to meet the processing quality standards needed to compete in global markets (Materechera and Scholes, 2022).

8.5 CONCLUSIONS FROM THE COMPARISON OF DEVELOPMENT SCENARIOS USING WEF NEXUS TOOLS

Based on benefits in terms of water, energy and food, switching some land to a high value crop would be the recommended action for this catchment out of the storylines tested. The investment to convert areas to macadamia orchards will need to be higher unless it is only in the form of subsidies, but the return on investment would be higher over a longer period. In reality, not all land will be converted to macadamias but the important motivation will be converting to more water-efficient crops and/or irrigation systems.

Economics was not the focus of this study, but detailed studies in the near future are recommended to take the findings of this research further. Positive impacts that could be created by the proposed dam (e.g. tourism opportunities) should also be carefully considered in making a holistic decision. To be more accurate, the study site could be divided into smaller areas for more granular calculations of water savings as a result of switching to more efficient irrigation systems or crops in different sub-catchments.

Other options that are being considered by the IUCMA for the Crocodile River Catchment include reducing domestic water demand, replacing irrigation canals with pipelines, removing alien invasive plants, and reducing afforestation. Reallocation of water resources using the compulsory licence process is being considered as a last resort. Most likely a combination of methods will need to be used. This WEF analysis lens has been used to demonstrate that by providing information, water managers can make more informed decisions based on the specific needs of the region. Water, energy and food are all scarce in this region, but in cases where there is an abundance of one or two resources, decision-making may be more straightforward.

CHAPTER 9: CONCLUSION AND RECOMMENDATIONS

9.1 GENERAL CONCLUSION

As much of the data required for the WEF nexus calculation is not readily available, and many of the private sector stakeholders are not willing to share sensitive data (such as turnover and employment rates), it became difficult to resolve the lack of data issues. The WEF nexus indicators were therefore calculated at provincial and municipal level instead of at catchment level.

The calculation of the WEF nexus indicators for the Crocodile River Catchment proved to be rather difficult due to limitations related to the availability of the data at different scales. As the Crocodile River flows from the Mpumalanga Highveld towards the Mozambique border, it passes through different district municipalities. Since most of the data needed for indicator calculations is collected at district level, this meant that it was not possible to do a comprehensive calculation for the whole of the catchment. As the boundaries of the catchment and the municipalities do not coincide. Another barrier was the different reporting time periods, so it was difficult to make a calculation for the current period, but only for a 2014-2019 period.

Stakeholders provided much useful information during the semi-structured interviews and focus group discussions about water governance across the Inkomati-Usuthu Catchment, highlighting the need for participatory stakeholder engagement in WEF nexus decision-making. However, processes of community validation of information gathered in participatory processes is lacking, showing that there is room for improvement in context-specific practical and policy implementation evaluation and planning. Some of the challenges include budget and human resource limitations to successful coordination across sectors. Four future scenarios were developed during the participatory stakeholder engagements for the Inkomati-Usuthu water management area – namely Scenario 1 “Adapt and Thrive – Agriculture in the Climate Crisis of 2035” (characterized by climate change – hotter, drier, floods); Scenario 2 “The Global Market Frontier of 2050” (characterized by socio-economic change, global competition, inequality, sustainable access, industry support); Scenario 3 “The Governance Imbalance of 2050 – The Fractured Nexus” (characterized by political/policy change, i.e. a lack of commitment from government, and change in political power); and Scenario 4 “The Stagnant Nexus of 2050” (characterized by business-as-usual management of the WEF nexus and depletion of resources).

There are several principles and perspectives considered central to implementing future WEF nexus framework concepts to influence policy and resource planning and development. It needs to be made more understandable and how the trade-off work, and one needs to ensure that accurate, reliable and valid data is available. Then the WEF nexus could be made adaptable to address many diverse situations and be able to be applied across various scales.

This first application of WEF nexus indicators to alternative scenarios in a strategic plan to increase the available water gave a good outcome. One can see that by building a dam at Mountain View, more nutritious food could be produced as well as making more water available for both irrigation and domestic consumption. The water, energy and food indicators showed that switching from sugarcane to a higher value crop such as macadamia is recommended for this catchment. Under macadamias there would be increased food and nutrient production, higher river flow, and similar biodiversity and electriicity availability. There would be more water available for irrigation so the land area to be irrigated could be expanded. When comparing planting macadamias to the scenario to build a dam, there were only lower values for the amount of water available for either domestic use or irrigation. Therefore, it can be recommended that the Inkomati-Usuthu Catchment Management Agency should proceed to negotiate with the agricultural sector to increase the planting of macadamia orchards or even investigate other waterwise crops.

9.2 RECOMMENDATIONS

It is recommended that the WEF nexus indices are calculated for the different district municipalities and not according to catchment or other geographical boundaries. Even though this may prove difficult to apply by the CMAs, it will at least be able to represent the situation according to the local governing districts and be applicable to their decision making. Other critical catchments should be selected, particularly where the energy sector is active, so that the WEF indices can be calculated and applied to their planning and decision making.

It is recommended that locally based WEF management teams should help ensure that WEF resources are managed in a holistic and equitable way. At present it appears that there is little coordination, even within a single sector, so this is a challenge for the future. It seems that stakeholders might have heard about the WEF nexus concept, but they do not really know how to apply it or use it in decision-making. Therefore, a series of workshops need to be held across all sectors to assist decision-makers to move from this conceptual thinking into a more practical mode of applying WEF nexus principles. This would mean starting from a low level of understanding and moving towards hands-on applications with their own data and information through a series of consultative workshops together with coordination across sectors.

The future scenarios should be tested for any different catchment, making adjustments and changes made where necessary after which specific aspects of the IDP should be addressed by applying the WEF indicators to possible interventions. For the IUWMA, following the successful comparison of three storylines using the WEF nexus indices, it is recommended that more detailed comparisons are made with additional data and information. As economics was not the focus of this study, it is recommended to take the findings of this research further and add a detailed economic assessment of such a change in crops and infrastructure before testing them with the relevant stakeholders.

It is also recommended that other strategic scenarios in the long-term development plan for the Crocodile River Catchment be put to the WEF nexus indicators test. In that way the IUCMA would be able to apply the outcomes of this research project to many future scenarios by using currently available data as well as expert and local knowledge about such aspects.

9.3 MOTIVATION FOR FURTHER RESEARCH

As this research project was the first to consider the WEF nexus from a mixed methods approach, it will be good if some of these types of results can be applied to a deeper analysis and replicated in other areas or important catchments, particularly those where the energy sector is utilising a good proportion of the available water. This will then assist managers in those areas to also apply the WEF nexus approach to their decision-making and planning, following the application of the future scenarios and calculation of the trade-offs and options using WEF nexus indices.

The "Facilitative Guideline for Policy-makers" which has been formulated (available as a separate document) can be used as a basis for studies in other important catchments around the country. This could assist in the establishment, routine management and planning activities in newly formed CMAs as well. The participatory formulation of appropriate scenarios that the users think are possible will assist in building the long-term goals for such CMAs. The calculation of the WEF nexus indices for such specific interventions give a different scientific perspective and validation to interventions.

The practical application of the WEF calculations to the scenarios in future planning has been a breakthrough in the use of the WEF nexus at Crocodile River Catchment level. Therefore, such applications need to be addressed for other scenarios in the long-term plan of the IUCMA. As it was only applied to the Crocodile River sub-catchment in this example (Chapter 8), it will be good to apply similar WEF indices to other sub-catchments within the IUCMA area such as the Usuthu River sub-catchment (Mkhondo and Msukoligwa Local Municipalities), where there are many coal-fired power stations using water. This will allow different perspectives to be explored when water is in demand by the energy sector. Another interesting application would be in the lower Nkomazi sub-catchment where agriculture is dominated by smallholder farmers. Application of WEF nexus indices to detailed scenarios for other catchments can also be useful in making decisions like water allocation to different sectors.

The application of WEF nexus equations and calculations to generate the indices for specific scenarios envisaged in strategic planning is a concrete way in which the WEF nexus assists water managers to make a reasonable assessment of the options available to them. Such calculations can be made using information available at provincial and/or local municipal level or obtained from expert consultants. Therefore, similar exercises between the expert researchers and the users need to be carried out in other catchments and/or district and local municipalities to address the conflicts and develop trade-offs.

9.4 LESSONS LEARNT

One major stumbling block was to integrate and match the spatial scales across the datasets. As the district and municipal boundaries differ from the physical and hydrological boundaries in the landscape, it is most difficult to translate the information from one to the other. Therefore, expert local knowledge is needed to make decisions about how to adjust and apply the information.

This project was carried out though the COVID-19 pandemic, so many lessons were learnt in how to conduct focus group discussion in virtual mode and not in-person. This proved to be possible, but was sometimes a challenge to connect via different platforms and stimulate good discussion and rapport with the group. Sometimes the poor mobile coverage and high cost of data became a challenge to be addressed particularly for stakeholders in rural areas.

Later in the project team members were able to attend the quarterly Catchment Management forums and present the concepts of WEF nexus to the stakeholders. This was a good opportunity to provide capacity building to stakeholders and community members on the concepts and the linkages between water, energy and food production sectors. It also provided a chance to evaluate the grassroot level opinions about the allocation of water across the sectors – urban, agriculture and energy. However, the team had to learn how to present such information and ask questions in a simple diagrammatic format for easier translation to the local language. These experiences and skills will remain with the team members as lessons learnt during this project.

Team members, from national and international organisations, had to learn to work together with members from both natural and social sciences. However, all were enriched by these challenges and were able to learn to value the others' perspectives. Therefore, the team members will carry these lessons and experiences with them into future projects.

The integration of natural scientific data and information with the social sciences information is a delicate road to travel to gain a broader perspective and holistic view of the situation. Once these concepts have been grasped by the various team members, they must be presented to stakeholders in an understandable manner during an open engagement platform. The stakeholders' reactions and reflections on emerging issues were recorded by means of surveys, questionnaires and discussions as mentioned in this report.

CHAPTER 10: CAPACITY BUILDING AND PUBLICATIONS

10.1 LIST OF STUDENTS AND INFORMATION REQUIRED BY WRC

There were four graduate students working on different aspects of this project. They are all black South African citizens and come from three different provinces. Two are enrolled for PhD degrees and two were studying for Masters degrees (Table 10.1).

Table 10.1 Graduate students working on the WEF nexus Crocodile River Catchment project

Full names	Qualification	Where registered	Age (y)	Gender	SA province of origin	Name of community	Settlement type
Bhekiwe Delisile Fakudze	PhD Agricultural Economics	University of Pretoria	35	Female	Gauteng	Mofolo village, Soweto	Peri-urban
Senzo Mduduzi Lukhele	MSc Engineering	University of the Witwatersrand	32	Male	Gauteng	Buffelspruit	Rural
Sylvia Machimana	Masters Communication	University of the Western Cape	51	Female	Limpopo	White River	Urban
Sibongile Nwabisa Masekwana	PhD Plant Science	University of Pretoria	41	Female	Eastern Cape	Mthatha	Urban

10.2 LIST OF PUBLICATIONS, PRESENTATIONS AND OTHER OUTPUTS

Scientific Articles:

Walker, S., Jacobs-Mata, I., Fakudze, B., Phahlane, M.O. & Masekwana, N. 2022. Applying the WEF nexus at a local level: A focus on catchment level. In: Mabhaudhi, T., Senzanje, A., Modi, A., Jewitt, G. & Massawe, F. (Eds) Water-Energy-Food Nexus Narratives and Resource Securities: A Global South Perspective. Elsevier, Ch. 7. pp 111-114. ISBN: 9780323912235. Publication date May 2022. https://shop.elsevier.com/books/water-energy-food-nexus-narratives-and-resource-securities/mabhaudhi/978-0-323-91223-5.

Masekwana, N., Walker, S. & Van der Laan, M., 2022. Application of Water-Energy-Food Nexus Framework Tools at Different Scales: Preliminary Assessment. Proceedings of ICID International Workshop of WG-WEF_N on "The Water-Energy-Food-Nexus: Implementation and Examples of Application", 4 October 2022, Adelaide Australia. https://icid-ciid.org/icid_data_web/Workshop_WFEN2022.pdf.

Walker, S., Jacobs-Mata, I., Masekwana, N., Fakudze, B. & Sawunyama, T., 2022. Catchment based Water-Energy-Food Nexus Assessment: Example of the Crocodile River Catchment, Mpumalanga, South Africa. Proceedings of ICID International Workshop of WG-WEF_N on "The Water-Energy-Food-Nexus: Implementation and Examples of Application", 4 October 2022, Adelaide Australia. https://icid-ciid.org/icid_data_web/Workshop_WFEN2022.pdf.

Presentations:

- Walker, S presented at Regional SADC Workshop on "Building Synergies in WEF Nexus Research", UKZN, Pietermaritzburg, South Africa, 5-6 March 2020.
- Presentations made at Crocodile Catchment Management Forum Meeting, Mpumalanga, South Africa, September 2020, November 2022, May 2023 and August 2023.
- Presentations made at Lower Komati and Sand River Catchment Management Forum Meetings, Mpumalanga, South Africa, November 2020 and November 2022.

- Jacobs-Mata, I presented "Pathways towards WEF Nexus Governance and Operationalization: Through a Systems Transformation Lens" at AURC Day 3, 27 May 2021, HSRC/WRC.
- Masekwana, N presented "The Application of Water-Energy-Energy Nexus Frameworks in Developing Agriculture" at Youth Indaba, June 2022.
- Jacobs-Mata, I presented "The WEF Nexus: A splintered approach trying to achieve integrated policy in a politicized world" at WRC WEF Nexus workshop at CSIR, 9 September 2022.
- Walker, S presented two papers at ICID International Workshop of WG-WEF_N on "The Water-Energy-Food-Nexus: Implementation and Examples of Application", 4 October 2022, Adelaide, Australia. (See abstracts in Appendix 4).
- Masekwana, N presented "A review on the Macadamia and Sugarcane crops in relation to Water-Energy-Food Nexus in Mpumalanga" at SANCID (South African National Committee on Irrigation & Drainage), 22 February 2023. (See abstract in Appendix 4).

REFERENCES

AGUDELO-VERA CM, LEDUC WRWA, MELS AR and RIJNAARTS HHM (2012) Harvesting urban resources towards more resilient cities. Resource Conservation Recycling **64** 3-12. https://doi.org/10.1016/j.resconrec.2012.01.014.

AMOS CC, RAHMAN A, KARIM F and GATHENYA J (2018) A scoping review of roof harvested 8rainwater usage in urban agriculture: Australia and Kenya in focus. Journal of Cleaner Production **202** 174-190. doi.org/10.1016/j.jclepro.2018.08.108.

AMUNDSEN C and SOHBAT E (2008) The untapped learning potential of CMC in higher education. In: KELSEY S and AMANT KST (eds.) *Handbook of research on computer mediated communication*, pp. 1-14. New York: Information Science Reference.

ANONYMOUS (2011) Mpumalanga Economic Growth and Development Path, Towards a more equitable and inclusive economy. http://www.dedtmpumalanga.gov.za/sites/default/files/documents/MEGDPv4.pdf.

ANONYMOUS (2012) About Mpumalanga Province http://www.mpumalanga.gov.za/about/province.htm.

ARC-NRE (Agricultural Research Council – Natural Resources and Engineering) (2022). Maps constructed by GeoInformatics Division, ARC-NRE Arcadia campus, by request.

ARY D, JACOBS L C, and RAZAVIEH A (1990). Introduction to Research in Education (4th ed.). Holt, Rinehart and Winston Inc., London: Harcourt Brace College.

BALZER T (2020) Briefing the Department of Water and Sanitation's Mpumalanga Provincial Implementation Plan. 9 October 2020. Available from: Department of Water and Sanitation (DWS).

BANDASON W, PARWADA C and MUSARA J (2021) Unlocking the potential of value chains as climate change resilience strategies: can macadamia nuts (*Macadamia integrifolia*) offer the gateway? South African Journal of Agricultural Extension **49(3)** 62-73. http://dx.doi.org/10.17159/2413-3221/2021/v49n3a12852.

BATE R, TREN R and MOONEY L (1999) *An econometric and institutional economic analysis of water use in the Crocodile River Catchment*. WRC Report No. 855/1/99. Water Research Commission, Pretoria.

BENNETT ND, NEWHAM LTH, CROKE BFW and JAKEMAN AJ (2007) Patching and disaccumulation of rainfall data for hydrological modelling. Presented at *MODSIM 2007 International Congress on Modelling and Simulation*, Christchurch, New Zealand. pp. 2520-2526. https://www.mssanz.org.au/MODSIM07/papers/45_s40/Patchings40_Bennett_.pdf.

BFAP (Bureau for Food and Agricultural Policy) (2012) Evaluating the Impact of Coal Mining on Agriculture in the Delmas, Ogies and Leandra Districts: A Focus on Maize Production. Bureau for Food and Agricultural Policy. BFAP Report 279783.

BHADURI A, RINGLER C, DOMBROWSKI I, MOHTAR R and SCHEUMANN W (2015) Sustainability in the water-energy-food nexus. Water International **40** 723-732. https://doi.org/10.1080/02508060.2015.1096110.

BIGGS EM, BRUCE E, BORUFF B, DUNCAN JMA, HORSLEY J, PAULI N, MCNEILL K, NEEF A, VAN OGTROP F, CURNOW J, HAWORTH B, DUCE S and IMANARI Y (2015) Sustainable development and the water-energy-food nexus: A perspective on livelihoods. Environmental Science and Policy **54** 389-397. https://doi.org/10.1016/j.envsci.2015.08.002.

BOUARAKIA O, ANDERS M, LINDEN VM, GRASS I, WESTPHAL C, TAYLOR PJ and FOORD SH (2023) Reduced macadamia nut quality is linked to wetter growing seasons but mitigated at higher elevations. Journal of Agriculture and Food Research 100569. https://doi.org/10.1016/j.jafr.2023.100569.

BOTHA L (2018) Securing the future of SA macadamias. Farmer's Weekly **2018** 18044, pp. 34-35. https://hdl.handle.net/10520/EJC-11fe2612dd.

BROUWER F, VAMVAKERIDOU-LYROUDIA L, ALEXANDRI E, BREMERE I, GRIFFEY M and LINDERHOF V (2018) The nexus concept integrating energy and resource efficiency for policy assessments: A comparative approach from three cases. Sustainability **10(12)** 4860. doi.org/10.3390/su10124860.

BRUINETTE K and CLAASENS T (2016) Managing the water balance: Water-technical paper. IMIESA **41(11)** 17-20. https://hdl.handle.net/10520/EJC197686.

CAI X, WALLINGTON K, SHAFIEE-JOOD M and MARSTON L (2018) Understanding and managing the food-energy-water nexus: Opportunities for water resources research. Advanced Water Resources **111** 259-273. https://doi.org/10.1016/j.advwatres.2017.11.014.

CARNEY D (2003) *Sustainable Livelihoods Approaches: Progress and Possibilities for Change*, Department for International Development (DFID), London, UK.

CASH DW, ADGER W., BERKES F, GARDEN P, LEBEL L, OLSSON P, PRITCHARD L and YOUNG O (2006) Scale and cross-scale dynamics: Governance and information in a multilevel world. Ecology and Society **11(2)** 8. https://doi.org/10.5751/ES-01759-110208.

CHANG Y, LI G, YAO Y, ZHANG L and YU C (2016) Quantifying the water-energy-food nexus: Current status and trends. Energies **9(2)** 1-17. doi:10.3390/en9020065.

CITY OF MBOMBELA (2015) Mbombela Local Economic Development Strategy Review. https://www.mbombela.gov.za/mbombela%20led%20review%20draft(latest).pdf. (Accessed 13 September 2021).

-CITY OF MBOMBELA (2018) City of Mbombela Annual Report 2017/2018. https://www.mbombela.gov.za/2017-2018%20final%20annual%20report%20final%202.pdf. (Accessed August 2021).

CITY OF MBOMBELA (2020) Final Integrated Development Plan (IDP) review 2021-2022. Municipal publication. https://www.mbombela.gov.za/approved%20final%20idp%20review%202020-%202021%20financial%20year.pdf. (Accessed October 2021).

CONWAY D, VAN GARDEREN EA, DERYNG D, DORLING S, KRUEGER T, LANDMAN W, LANKFORD B, LEBEK K, OSBORN T, RINGLER C, THURLOW J, ZHU T and DALIN C (2015) Climate and southern Africa's water-energy-food nexus. Nature Climate Change **5(9)** 837-846. doi:10.1038/nclimate2735.

CSIR (Council for Scientific and Industrial Research) (2017) Land and Water Use. https://www.csir.co.za/sites/default/files/Documents/4.%20CSIR%20CGA_A1_HIGHRES_Inkomati.pdf. (Accessed August 2021).

DAFF (Department of Agriculture, Forestry and Fisheries) (2012) A profile of the South African macadamia nuts market value chain. (https://www.agmrc.org/media/cms/Macadamia_Nuts_Value_Chain__Profile_CB794B737CE79.pdf. (Accessed 26 April 2023).

DAHER BT and MOHTAR RH (2015) Water-energy-food (WEF) Nexus tool 2.0: guiding integrative resource planning and decision-making. Water International **40** 748-771. doi: 10.1080/02508060.2015.1074148.

DAHER B and MOHTAR RH (2021) Water-energy-food sustainable development goals in Morocco. In: LEAL FILHO W, AZUL AM, BRANDLI L, LANGE SALVIA A and WALL T (eds.) *Clean Water and Sanitation. Encyclopaedia of the UN Sustainable Development Goals.* Cham: Springer. doi:10.1007/978-3-319-70061-8_133-1.

DAHER B, LEE SH, ASSI A, MOHTAR RH and MOHTAR R (2017) Modeling the Water-Energy-Food Nexus: A 7-Question Guideline. In: ABDUL SALAM P, SHRESTHA S, VISHNU PRASAD PANDEY VP and ANIL KA (eds.) *Water-Energy-Food Nexus: Principles and Practices*, pp. 57-66. American Geophysical Union. John Wiley & Sons. https://doi.org/10.1002/9781119243175 https://agupubs.onlinelibrary.wiley.com/doi/10.1002/9781119243175.ch6.

DAHER BT and MOHTAR RH (2015) Water-energy-food (WEF) nexus tool 2.0: Guiding integrative resource planning and decision-making. Water International **40** 748-771. https://doi.org/10.1080/02508060.2015.1074148.

DAI J, WU S, HAN G, WEINBERG J, XIE X, WU X, SONG X, JIA B, XUE W and YANG Q (2018) Water-energy nexus: A review of methods and tools for macro-assessment. Applied Energy **210** 393-408. doi:10.1016/j.apenergy.2017.08.243.

DEA (Department of Environmental Affairs) (2014) GHG National Inventory Report: 2000-2010. http://www.saaqis.org.za/. (Accessed February 2022).

DE GRENADE R, HOUSE-PETERS L, SCOTT CA, THAPA B, MILLS-NOVOA M, GERLAK A and VERBIST K (2016) The nexus: Reconsidering environmental security and adaptive capacity. Current Opinion Environmental Sustainability **21** 15-21. https://doi.org/10.1016/j.cosust.2016.10.009.

DEDT (Department of Economic Development and Tourism) (2019) *Public Sector Economist Forum, Kimberley, Northern Cape, South Africa.* Available from: Mpumalanga Department of Economic Development and Tourism Annual Performance Plan 2020/2021.

DEDT (Department of Economic Development and Tourism) (2020). Mpumalanga Department of Economic Development and Tourism Annual Report 2019-2020, Vote 6, Province of Mpumalanga.

DEDT (Department of Economic Development and Tourism) (2021) Mpumalanga Department of Economic Development and Tourism Annual Performance Plan 2020/2021, 4 September 2020.

DFFE (Department of Forestry, Fisheries and the Environment) (2021) National GHG Inventory Report: 2017. https://www.dffe.gov.za/sites/default/files/docs/nir-2017-report.pdf. (Accessed February 2022).

DLG (Department of Local Government) (2009) Mpumalanga on electricity usage. https://www.gov.za/mpumalanga-electricity-usage. (Accessed 2 March 2009).

DONNENFELD Z, CROOKES C and HEDDEN S (2018) A delicate balance: water scarcity in South Africa. Institute for Security Studies. Mpumalanga, South Africa. https://www.green-cape.co.za/assets.

DWA (Department of Water Affairs) (2009) Water for Growth and Development Framework. https://www.dws.gov.za/WFGD/documents/WfGDv6Nov21.pdf.

DWA (Department of Water Affairs) (2013a) *Business case for the Inkomati-Usuthu Catchment Management Agency*. Pretoria, South Africa.

DWA (Department of Water Affairs) (2013b) *National Water Resources Strategy 2. Government of South Africa*. Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry) (1997) White Paper on a National Water Policy for South Africa. https://www.gov.za/sites/default/files/gcis_document/201409/nwpwp.pdf.

DWAF (Department of Water Affairs and Forestry) (2014) Water Requirements and Availability Reconciliation Strategy for the Mbombela Municipal Area: Current and future water requirements and water resources (final) (accessed 30 August 2023) https://www.dws.gov.za/iwrp/Mbombela/Documents/Water%20Requirements%20&%20Water%20Resources%20Report%20Final%20signed.pdf,

DWS (Department of Water and Sanitation) (2021a) *Continuation of water requirements and availability reconciliation strategy study for the Mbombela municipal area.* Infrastructure and Cost Assessment Report. DWS Report No. P WMA https://www.dws.gov.za/iwrp/Mbombela/Documents/PDF%20SIGNED%20DOCUMENTS/6%20Infrastructure%20and%20Cost%20Assessment.pdf 154 pp.

DWS (Department of Water and Sanitation) (2021b) Continuation of water requirements and availability reconciliation strategy study for the Mbombela municipal area. Extended Executive Summary. https://www.dws.gov.za/iwrp/Mbombela/Documents/PDF%20SIGNED%20DOCUMENTS/8%20Extended%20Executive%20Summary%20FINAL-compressed.pdf, 16 pp (Accessed 26 April 2023).

EBENSTEIN A, FAN M, GREENSTONE M, HE G and ZHOU M (2017) New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. Proceedings National Academy Sciences **114(39)** 10384-10389. https://doi.org/10.1073/pnas.1616784114.

EL-HAGGAR S (2005) Rural and developing country solutions. In: AGARDY FJ and NEMEROW NL (eds.) *Environmental Solutions*, Academic Press, Chapter 13, pp. 313-400, ISBN 9780120884414, https://doi.org/10.1016/B978-012088441-4/50015-0.

ENDO A, BURNETT K, ORENCIO PM, KUMAZAWA T, WADA CA, ISHII A, TSURITA I and TANIGUCHI M (2015) Methods of the water-energy-food nexus. Water **7** 5806-5830; doi:10.3390/w7105806.

ENDO A, YAMADA M, MIYASHITA Y, SUGIMOTO R, ISHII A, NISHIJIMA J, FUJII M, KATO T, HAMAMOTO H, KIMURA M, KUMAZAWA T and QI J (2020) Dynamics of water-energy-food nexus methodology, methods, and tools. Current Opinion in Environmental Science and Health **13** 46-60. doi.org/10.1016/j.coesh.2019.10.0042468-5844/.

ENGSTRÖM RE, HOWELLS M, DESTOUNI G, BHATT V, BAZILIANA M and ROGNER HH (2017) Connecting the resource nexus to basic urban service provision – with a focus on water-energy interactions in New York City. Sustainable Cities and Society **31** 83-94. doi.org/10.1016/j.scs.2017.02.007.

ERCIN AE, ALDAYA M and HOEKSTRA A (2011) Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage. Water Resource Management **25** 721-741. doi.org/10.1007/s11269-010-9723-8.

FAO (Food and Agriculture Organization) (2014) *Walking the nexus talk: Assessing the water-energy-food nexus in the context of the sustainable energy for all initiative*. http://www.fao.org/3/a-i3959e.pdf. (Accessed 30 July 2020).

FAO (Food and Agriculture Organization) (2020) *Water Uses Database* (Accessed 24 July 2020) http://www.fao.org/nr/water/aquastat/water_use/index.stm.

FERROUKHI R, NAGPAL D, LÓPEZ-PEÑA A, HODGES T, MOHTAR R, DAHER B, MOHTAR S and KEULERTZ M (2015) Renewable Energy in the Water, Energy and Food Nexus, IRENA Technical Report, 124 pp.

FERNÁNDEZ-RÍOS A, LASO J, CAMPOS C, RUIZ-SALMÓN I, HOEHN D, CRISTÓBAL J, BATLLE-BAYER L, BALA A, FULLANA-I-PALMER P, PUIG R, ALDACO R and MARGALLO M (2021) Towards a Water-Energy-Food (WEF) nexus index: A review of nutrient profile models as a fundamental pillar of food and nutrition security. Science of the Total Environment **789** 147936, doi:10.1016/j.scitotenv.2021.147936.

FIGUEROA MEK, RANI DL AND MANJU G (2003) Communication for social change: An integrated model for measuring the process and its outcomes. Lewisnline www.pesquisa.bvsalud.org.

GALE NK, HEATH G and CAMERON E (2013) Using the framework method for the analysis of qualitative data in multi-disciplinary health research. BMC Medical Research Methodology **13** 117. https://doi.org/10.1186/1471-2288-13-117.

GBETIBOUO GA and HASSAN RM (2005) Measuring the economic impact of climate change on major South African field crops: A Ricardian approach. Global and Planetary Change **47(2-4)** 143-152. https://doi.org/10.1016/j.gloplacha.2004.10.009.

GENIS A (2020) GTAC/CBPEP/EY project on the employment-intensive rural land reform in South Africa: policies, programmes and capacities. Commodity study – Subtropical fruit production by small-scale farmers in South Africa and employment-intensive land reform. https://www.gtac.gov.za/resource/gtac-cbpep-eu-project-on-employment-intensive-rural-land-reform-in-south-africa-policies-programmes-and-capacities-commodity-study-subtropical-fruit-production-by-small-scale-farmers-in-south-af/. (Accessed 26 April 2023).

GERBENS-LEENES PW, MEKONNEN MM and HOEKSTRA AY (2013) The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. Water Resources Industry **1** 25-36. https://doi.org/10.1016/j.wri.2013.03.001.

GIAMPIETRO M, MAYUMI K and RAMOS-MARTIN J (2009) Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. Energy **34(3)** 313-322. https://doi.org/10.1016/j.energy.2008.07.020.

GLASER BG (2007) All is data. Grounded Theory Review **6(2)** 1-22. https://groundedtheoryreview.com/2007/03/30/1194/.

GRAHAM JW (2009) Missing data analysis: Making it work in the real world. Annual Review Psychology **60** 549-576. doi: 10.1146/annurev.psych.58.110405.085530.

GREEN CAPE (2021). Water Market Intelligence Report. https://www.green-cape.co.za/assets/WATER_MIR.pdf (Accessed 31st March 2021).

GRIMM NB, FAETH SH, GOLUBIEWSKI NE, REDMAN CL, WU J, BAI X and BRIGGSET JM (2008) Change and the ecology of cities. Science **319** 756-760. doi: 10.1126/science.1150195.

GUPTA AD (2017) Water-Energy-Food (WEF) nexus and sustainable d]evelopment. In Abdul Salam P, Shrestha S, Pandey VP, and Anal AK (Eds) Water-Energy-Food Nexus: Principles and Practices, pp.221-241. American Geophysical Union – Book Series: Geophysical Monograph Series https://doi.org/10.1002/9781119243175.ch19.

GUSH MB and TAYLOR NJ (eds.) (2014) *The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling*. Report 1770/2/14, Water Research Commission, Pretoria, South Africa.

HOFF H (2011) Understanding the nexus – background paper. In: *Bonn 2011 Conference: The Water Energy and Food Security Nexus*. Environment Institute, Stockholm.

HOOLOHAN C, LARKIN A, MCLACHLAN C, FALCONER R, SOUTAR I, SUCKLING J and YU D (2018) Engaging stakeholders in research to address water-energy-food (WEF) nexus challenges. Sustainability Science **13** 1415-1426. https://doi.org/10.1007/s11625-018-0552-7.

HOWELLS M, HERMANN S, WELSCH M, BAZILIAN M, SEGERSTRÖM R, ALFSTAD T, GIELEN D, ROGNER H, FISCHER G and VAN VELTHUIZEN H (2013) Integrated analysis of climate change, land-use, energy and water strategies. Nature Climate Change **3** 621. https://doi.org/10.1038/nclimate1789.

HUANG D, LI G, SUN C and LIU Q (2020) Exploring interactions in the local water-energy-food nexus (WEF-Nexus) using a simultaneous equations model. Science of the Total Environment **703** 135035. doi.org/10.1016/j.scitotenv.2019.135034.

IRENA (International Renewable Energy Agency) (2015) *Renewable energy in the water, energy and food nexus.* http://www.irena.org/DocumentDownloads/Publications/IRENA_Water_Energy_Food_Nexus_2015.pdf.

IUCMA (Inkomati-Usuthu Catchment Management Agency) (2020). Annual Performance Plan, 2019-2020. https://iucma.co.za/iucma-documents/.

JACKSON B (2014) An adaptive operational water resources management framework for the Crocodile River catchment, South Africa. MSc: Hydrology. University of KwaZulu-Natal, Pietermaritzburg. 219 pp.

JACOBS-MATA I, MUKUYU P and DINI J (2021) A review of trends in scientific coverage of water governance in South Africa and what this means for agenda setting of public investment in water governance R&D. Water SA **47(1)** 10-23. doi: 10.17159/wsa/2021.v47.i1.9441.

JARMAIN C, SINGELS A, BASTIDAS-OBANDO E, PARASKEVOPOULOS A, OLIVIER F, VAN DER LAAN M, TAVERNA-TURISAN D, DLAMINI M, MUNCH Z, BASTIAANSSEN W, ANNANDALE J, EVERSON C, SAVAGE M and WALKER S (2014) *Water Use Efficiency of Selected Irrigated Crops Determined with Satellite Imagery*. WRC Report No. TT 602/14, ISBN 978-1-4312-0573-8. Water Research Commission, Pretoria.

JEFFREY SJ, CARTER JO, MOODIE KB and BESWICK AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software **16** 309-330. https://doi.org/10.1016/S1364-8152(01)00008-1.

JIANG S (2017) Scientific concept of water-energy nexus and coupling simulation, PhD thesis. China Institute of Water Resources and Hydropower Research, Beijing, China.

KADDOURA, S and EL KHATIB S (2017) Review of water-energy-food nexus tools to improve the nexus modelling approach for integrated policy making. Environmental Science and Policy **77** 114-121. https://doi.org/10.1016/j.envsci.2017.07.007.

KARIM N, MOHAMMAD D and DAHER H (2021) Evaluating the potential of a Water-Energy-Food nexus approach toward the sustainable development of Bangladesh. Water **13(3)** 366. https://doi.org/10.3390/w13030366.

KARNIB A (2017) A quantitative assessment framework for water, energy and food nexus. Computational Water, Energy, and Environmental Engineering **6** 11-23. doi: 10.4236/cweee.2017.61002.

KEMP J, DEAN C and CHODACKI J (2018) Can richer metadata rescue research? The Serials Librarian **74(1-4)** 207-211. doi.org/10.1080/0361526X.2018.1428483.

KENWAY SJ, LANT PA, PRIESTLEY A and DANIELS P (2011) The connection between water and energy in cities: A review. Water Science Technology 63(9) 1983-1990. doi: 10.2166/wst.2011.070.

KLEYNHANS CJ, THIRION C, ROUX F, HOFFMANN A, MARAIS H and DIEDERICKS G (2013) Ecostatus of the Crocodile River Catchment, Inkomati River System. Compiled by Mpumalanga Tourism and Parks Agency Scientific Services: Aquatic and Herpetology 10.13140/RG.2.1.1157.3208.

KOK K, PATEL M, ROTHMAN DS and QUARANTA G (2006) Multiscale narratives from an IA perspective. Part 2. Participatory local scenario development. Futures **38** 261-284. https://doi.org/10.1016/j.futures.2005.07.006.

KRANTZ L (2001) *The Sustainable Livelihood Approach to Poverty Reduction: An Introduction.* Swedish International Development Cooperation Agency (SIDA), Stockholm, Sweden.

KROLL F, MÜLLER F, HAASE D and FOHRER N (2012) Rural-urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy **29** 521-535. https://doi.org/10.1016/j.landusepol.2011.07.008.

LARCOM S and VAN GEVELT T (2017) Regulating the water-energy-food nexus: Interdependencies, transaction costs and procedural justice. Environmental Science & Policy **72** 55-64. https://doi.org/10.1016/j.envsci.2017.03.003.

LAWFORD RG (2019) A design for a data and information service to address the knowledge needs of the Water-Energy-Food (W-E-F) nexus and strategies to facilitate its implementation. Frontiers in Environmental Science **7**. doi:10.3389/fenvs.2019.00056.

LE ROUX B, VAN DER LAAN M, GUSH MB and BRISTOW K (2018) Comparing the usefulness and applicability of different water footprint methodologies for sustainable water management in agriculture. Irrigation and Drainage **67(5)** 790-799. doi: 10.1002/ird.2285.

LEVISTON Z, WALKER I, GREEN M and PRICE J (2018) Linkages between ecosystem services and human wellbeing: A Nexus Webs approach. Ecological Indicators **93** 658-668. https://doi.org/10.1016/j.ecolind.2018.05.052.

LÖTTER MC (2015) Technical Report for the Mpumalanga Biodiversity Sector Plan – MBSP 2015. Mpumalanga Parks and Tourism Agency. https://conservationcorridor.org/cpb/Lotter_2015.pdf.

MABHAUDHI T, CHIMONYO VGP, HLAHLA S, MASSAWE F, MAYES S, NHAMO L and MODI AT (2019a) Prospects of orphan crops in climate change. Planta **250** 695-708. doi.org/10.1007/s00425-019-03129-y.

MABHAUDHI T, MPANDELI S, MADHLOPA A, MODI AT, BACKEBERG G and NHAMO L (2016) Southern Africa's water-energy nexus: Towards regional integration and development. Water **8** 235. https://doi.org/10.3390/w8060235.

MABHAUDHI T, NHAMO L, MPANDELI S, NHEMACHENA C, SENZANJE A, SOBRATEE N, CHIVENGE PP, SLOTOW R, NAIDOO D, LIPHADZI S and MODI AT (2019b) The Water-Energy-Food Nexus as a tool to transform rural livelihoods and well-being in Southern Africa. International Journal of Environmental Research Public Health **16(16)** 2970. doi:10.3390/ijerph16162970.

MABHAUDHI T, NHAMO L, CHIBARABADA TP, MABAYA G, MPANDELI S, LIPHADZI S, SENZANJE A, NAIDOO D, MODI AT and CHIVENGE PP (2021) Assessing progress towards sustainable development goals through nexus planning. Water **13** 1321. https://doi.org/10.3390/w13091321.

MACHIMANA S (2023) Application of Science Communication Methods to Facilitate the Process of Stakeholder Engagement, Inkomati-Usuthu Catchment in Mpumalanga, South Africa. M Phil Integrated Water Resources Management, University of the Western Cape, 90pp.

MACK N, MACQUEEN M, GUEST G, NAMEY E and WOODSONG C (2005) Qualitative Research Methods: A data collector's field guide. North Carolina. Family Health International. http//www.fhi.org.

MANNAN M, AL-ANSARI T, MACKEYHR and AL-GHAMDI SG (2018) Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment. Journal of Cleaner Production **193** 300e314. doi.org/10.1016/j.jclepro.2018.05.050.

MARTINEZ-HERNANDEZ E, LEACH M and YANG A (2017) Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. Applied Energy **206** 1009-1021. https://doi.org/10.1016/j.apenergy.2017.09.022.

MASHABATU M (2022) determining crop coefficients for irrigated fruit tree crops using readily available data sources. MSc. University of the Western Cape, Dept of Earth Sciences, https://etd.uwc.ac.za/bitstream/handle/11394/9106/mashabatu_m_nsc_2022.pdf?sequence=1&isAllowed=y.

MATERECHERA F and SCHOLES M (2022) Scenarios for sustainable farming systems for macadamia nuts and mangos using a systems dynamics lens in the Vhembe District, Limpopo South Africa. Agriculture **12** 1724. https://doi.org/10.3390/agriculture12101724.

MATTHEWS B and ROSS L (2010). *Research Methods: A Practical Guide for the Social Sciences.* Harlow, UK: Pearson Education.

MCCARL BA, YANG Y, SCHWABE K, BERNARD AE, ALAM HM, CLAUDIA R and EFSTRATIOS NP (2017a) Model use in WEF nexus analysis: A review of issues. Current Sustainable Renewable Energy Report **4** 144-152. https://doi.org/10.1007/s40518-017-0078-0.

MCCARL BA, YANG Y, SRINIVASAN R, PISTIKOPOLOUS EN and MOHTAR RH (2017b) Data for WEF nexus analysis: A review of issues. Current Sustainable/Renewable Energy Reports **4** 137-143. https://doi.org/10.1007/s40518-017-0083-3.

MCGINNIS MD (2011) Networks of adjacent action situations in polycentric governance. Policy Studies Journal **39(1)** 51-78. doi:10.1111/j.1541-0072.2010.00396.

MCLOUGHLIN C, RIDDELL E, PETERSEN R and VENTER J (2021) Adaptive and transformative learning in environmental water management: Implementing the Crocodile River's ecological reserve in Kruger National Park, South Africa. Koedoe ***63*(1)**. doi: doi.org/10.4102/koedoe.v63i1.1663.

MCKENZIE R, SIQALABA ZN and WEGELIN WA (2012) *The State of Non-Revenue Water in South Africa*. WRC Report No. TT 522/12. Water Research Commission, Pretoria.

MOELETSI ME, MYENI L, KAEMPFFER LC, VERMAAK D, DE NYSSCHEN G, HENNINGSE C, NEL I, ROWSWELL D, (2022) Climate dataset for South Africa by the Agricultural Research Council. Data **7** 117. https://doi.org/10.3390/data7080117.

MOHTAR RH, AOUN M, DAHER B, LASPIDOU CS, KIM H and SHARMA VK (2023) Editorial: Water-Energy-Food health solutions and innovations for low carbon, climate-resilient drylands. Frontiers in Environmental Science **11** 1153671. doi:10.3389/fenvs.2023.1153671.

MOHTAR RH and DAHER B (2016) Water-Energy-Food Nexus Framework for facilitating multi-stakeholder dialogue. Water International **41(5)** 655-661. doi: 10.1080/02508060.2016.1149759.

MONYEI CG and ADEWYUMI AO (2017) Demand side management potentials for mitigating energy poverty in South Africa. Energy Policy **111** 298-311. http://dx.doi.org/10.1016/j.enpol.2017.09.039.

MOROKONG T, BLIGNAUT J, NKAMBULE N-P, MUDHAVANHU S and VUNDLA T (2016) Clearing invasive alien plants as a cost-effective strategy for water catchment management: The case of the Olifants river catchment, South Africa. South African Journal of Economic and Management Sciences **19(5)** 774-787. http://dx.doi.org/10.17159/2222-3436/2016/v19n5a6.

MPANDELI S, NAIDOO D, MABHAUDHI T, NHEMACHENA C, NHAMO L, LIPHADZI S, HLAHLA S and MODI A (2018) Climate change adaptation through the water-energy-food nexus in Southern Africa. International Journal of Environmental Research and Public Health **15** 2306. doi:103390/ijerph15102306.

MPANDELI S, NESAMVUNI E and MAPONYA P (2015) Adapting to the impacts of drought by smallholder farmers in Sekhukhune District in Limpopo Province, South Africa. Journal of Agricultural Science **7(2)** 115-124. doi: 10.5539/jas.v7n2pxx.

MPUMALANGA GREEN CLUSTER AGENCY (2021) *Mpumalanga Water Market Intelligence Opportunity Brief 2021*. https://www.green-cape.co.za/assets/Uploads/04-10-2021/MPUMALANGA_2021-WATER_MIR_FINAL_DIGITAL.pdf. (Accessed 4 October 2021).

MUSSA (Municipal Strategic Self-Assessment) (2015) Municipal Strategic Self-Assessment of WSAs in Mpumalanga Final Draft Report, DWS, Water Services Planning and Information: Business Intelligence Team, 60 pp.

NESS B, URBEL-PIIRSALU E, ANDERBERG S and OLSSON L (2007) Categorising tools for sustainability assessment. Ecological Economics **60** 498-508. https://doi.org/10.1016/j.ecolecon.2006.07.023.

NHAMO L, MABHAUDHI T and MAGOMBEYI M (2016) Improving water sustainability and food security through increased crop water productivity in Malawi. Water **8** 411. https://doi.org/10.3390/w8090411.

NHAMO L, MABHAUDHI T and MODI AT (2019a) Preparedness or repeated short-term relief aid? Building drought resilience through early warning in southern Africa. Water SA **45(1)** 75-85. http://dx.doi.org/10.4314/wsa.v45i1.09.

NHAMO L, MABHAUDHI T, MPANDELI S, DICKENS C, NHEMACHENA C, SENZANJE A, NAIDOO D, LIPHADZI S and MODI A (2020a) An integrative analytical model for the water-energy-food nexus: South Africa case study. Environmental Science & Policy **109** 15-24. https://doi.org/10.1016/j.envsci.2020.04.010.

NHAMO L, MABHAUDHI T, MPANDELI S, NHEMACHENA C, SENZANJE A, NAIDOO D, LIPHADZI S and MODI AT (2019b) Sustainability indicators and indices for the water-energy-food nexus for performance assessment: WEF nexus in practice – South Africa case study. Preprint 2019050359. doi: 10.20944/preprints201905.0359.v1.

NHAMO L, MATCHAYA G, MABHAUDHI T, NHLENGETHWA S, NHEMACHENA C and MPANDELI S (2019c) Cereal production trends under climate change: Impacts and adaptation strategies in Southern Africa. Agriculture **9** 30. doi: 10.3390/agriculture9020030.

NHAMO L and NDLELA B (2021) Nexus planning as a pathway towards sustainable environmental and human health post Covid-19. Environmental Research **192** 110376. https://doi.org/10.1016/j.envres.2020.110376.

NHAMO L, NDLELA B, NHEMACHENA C, MABHAUDHI T, MPANDELI S and MATCHAYA G (2018) The water-energy-food nexus: Climate risks and opportunities in southern Africa. Water **10** 567. doi:10.3390/w10050567.

NHAMO L, NDLELA B, MPANDELI S and MABHAUDHI T (2020b) The Water-Energy-Food Nexus as an adaptation strategy for achieving sustainable livelihoods at a local level. Sustainability **12(20)** 8582. https://doi.org/10.3390/su12208582.

NHAMO L, NAIDOO D, MPANDELI S, HLOPHE-GININDZA S, and LIPHADZ S (2021) A framework for sustainable land redistribution to ensure water and land tenure security: Focus on South Africa. South African Water Research Commission Working Paper Jan 2021. doi: 10.13140/RG.2.2.26724.60801.

NHAMO L, NDLELA B, MPANDELI S and MABHAUDHI T (2023) Advances in water research: Enhancing sustainable water use in irrigated agriculture in South Africa, In: *Progress in Sustainable Development* 1st Ed., Chapter 8. Elsevier. doi: 10.1016/B978-0-323-99207-7.00007-5.

OECD STATS (2018) Organisation for Economic Co-Operation and Development. http://stats.oecd.org/ (Accessed January 2022).

OOSTHUIZEN LK, BOTHA PW, GROVE B and MEIRING JA (2005) Cost-estimating procedures for drip-, micro-and furrow-irrigation systems. Water SA **31(3)** 403-406. doi: 10.4314/wsa.v31i3.5214.

OSTROM E (1990) *Governing the commons: The evolution of institutions for collective action.* Cambridge, MA: Cambridge University Press.

PALMER CG, GRIFFIN NJ, SCHERMAN PA, DU TOIT D, MANDIKIANA B and POLLARD S (2013) *A Preliminary Examination of Water Quality Compliance in a Selected Lowveld River: Towards Implementation of the Reserve*. WRC Report No. KV 306/12, ISBN No 978-1-4312-0355-0. Water Research Commission, Pretoria.

PARSHOTAM A (2018) *Cultivating Smallholder Inclusion in Southern Africa's Macadamia*. South African Institute of International Affairs: Pretoria, South Africa. Occasional Paper 278. https://www.jstor.org./stable/resrep28391.

PATEL M, KOK K and ROTHMAN DS (2007) Participatory scenario construction in land use analysis: an insight into the experiences created by stakeholder involvement in the Northern Mediterranean. Land Use Policy **24** 546-561. doi:10.1016/j.landusepol.2006.02.005.

PATTINSON EM, COTTERILL ST and LEYLAND S (2017) Sources of self-efficacy in springboard and high board diving: A qualitative investigation. Sport and Exercise Psychology Review **13(2)** 80-91 doi: 10.53841/bpssepr.2017.13.1.80.

PERRONE D, MURPHY J and HORNBERGER GM (2011) Gaining perspective on the water energy nexus at the community scale. Environmental Science and Technology **45** 4228-4234. https://doi.org/10.1021/es103230n.

PRYOR SW, SMITHERS J, LYNE P and VAN ANTWERPEN R (2017) Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. Journal of Cleaner Production **141** 137-145. http://dx.doi.org/10.1016/j.jclepro.2016.09.069.

PURWANTO A, SUNSIK J, SURYADI F and DE FRAITURE C (2021) Water-Energy-Food Nexus: Critical Review, Practical Applications, and Prospects for Future Research. Sustainability **13**. 10.3390/su13041919.

RASUL G and NEUPANE N (2021) Improving policy coordination across the water, energy, and food, sectors in South Asia: A framework. Frontiers in Sustainable Food Systems **5** 602475. doi.org/10.3389/fsufs.2021.602475.

RINGLER C (2017) *Investments in irrigation for global food security*. International Food Policy Research Institute, Washington DC, U.S.A.

ROBINSON J (2003). Future subjunctive: Backcasting as social learning. Futures **35(8)** 839-856. https://doi.org/10.1016/S0016-3287(03)00039-9.

RUCH W (2014) Measuring poverty in SA. Fieldworker **5(3)** June/July 2014. http://www.statssa.gov.za/wp-content/uploads/2014/07/Fieldworker-Low-Res-June-2014.pdf

RYAN GW and BERNARD HR (2003) Techniques to identify themes. Field Methods **15(1)** 85-109. https://doi.org/10.1177/1525822X022395.

SALDAÑA J (2009) *The coding manual for qualitative researchers*. Sage Publications Ltd.

SALMORAL G and YAN X (2018) Food-energy-water nexus: A life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment UK. Resource Conservation Recycling **133** 320-330. https://doi.org/10.1016/j.resconrec.2018.01.018.

SAMAC (Macadamias South Africa) (undated) What have we learned? https://samac.org.za/wp-content/uploads/2023/04/SAMAC-What-Have-We-Learned.pdf (accessed 30 August 2023).

SAMAC (Macadamias South Africa) (2020a) Statistics on the Southern African Macadamia Industry. Macadamias South Africa. https://www.samac.org.za/industry-statistics/.

SAMAC (Macadamias South Africa) (2020b) An overview of the South African Macadamia Industry. Macadamias South Africa.

SAMAC (Macadamias South Africa) (2016) China's Massive Macadamia Market. Macadamias South Africa.

SAMAC (Macadamias South Africa) (2021) Statistics on the South African Macadamia Industry. Macadamias South Africa.

SASRI (South African Sugar Research Institute) (2017) Information Sheet. 5.8 Irrigation Systems Selection, https://sasri.org.za/information-sheets/.

SHABALALA M, TOUCHER M and CLULOW A (2022) The Macadamia bloom – What are the hydrological implications? Scientia Horticulturae **292** 110628, https://doi.org/10.1016/j.scienta.2021.110628..

SHABALALA ZP, MOELETSI ME, TONGWANE MI and MAZIBUKO SM (2019) Evaluation of infilling methods for time series of daily temperature data: Case study of Limpopo Province, South Africa. Climate **7(7)** 86. https://doi.org/10.3390/cli7070086.

SHACKLETON C, PAUMGARTEN F and COCKS M (2008) Household attributes promote diversity of tree holdings in rural areas, South Africa. Agroforestry Systems **72(3)** 221-230. https://doi.org/10.1007/s10457-007-9066-5.

SHAPIRO G and MARKOFF G. (1997). Text analysis for the social sciences. In: ROBERTS CW and MAHWAH NJ (eds.) *Methods for drawing statistical inferences from text and transcripts,* pp. 9-31. Lawrence Erlbaum Associates.

SIBULALI A (2018) *Analysing the competitive performance of the South African subtropical fruit Industry.* MSc dissertation, Stellenbosch University, South Africa.

SIBULALI A (2020) *Market Intelligence Report: Macadamia Nuts Industry*. Western Cape Department of Agriculture Report, South Africa.

SIBULALI A (2021) *Market Intelligence Report: Macadamia Nuts Industry.* Western Cape Government Department of Agriculture (https://www.elsenburg.com/wp-content/uploads/2022/03/2021-Macadamias-MIR.pdf. (Accessed 26 April 2023).

SIDDIQI A and FLETCHER S (2015) Energy intensity of water end-uses. Current Sustainable Renewable Energy Report **2(1)** 25-31. doi: 10.1007/s40518-014-0024-3.

SIMPSON G and BERCHNER M **(**2017) Measuring integration – towards a water-energy-food nexus index. The Water Wheel **16** 22-23. https://hdl.handle.net/10520/EJC-5656d40ae.

SIMPSON GB, BADENHORST J, JEWITT GP, BERCHNER M and DAVIES E (2019) Competition for land: The Water-Energy-Food nexus and coal mining in Mpumalanga Province, South Africa. Frontiers in Environmental Science **7**. DOI: 10.3389/fenvs.2019.00086.

SRIGIRI SR and DOMBROWSKY I (2021) Conceptual and methodological framework for analysis. In: *Governance of the water-energy-food nexus for an integrated implementation of the 2030 Agenda.* Discussion Paper, No. 2/2021, ISBN 978-3-96021-139-6, Deutsches Institut für Entwicklungspolitik (DIE), Bonn, http://dx.doi.org/10.23661/dp2.2021.

STATSSA (Statistics South Africa) (2011) Census http://www.statssa.gov.za/?page_id=993andid=mbombela-municipality (Accessed 16 September 2021).

STATSSA (Statistics South Africa) (2015) General household survey 2014. Statistics South Africa **174**.

STATSSA (Statistics South Africa) (2016a) Water and Sanitation: In-depth Analysis of the General Household Survey 2002-2015 and Community Survey 2016 Data. Statistics South Africa: GHS Series Volume **VIII** 106.

STATSSA (Statistics South Africa) (2016b) Electricity Generated and Available for Distribution (Preliminary), Statistics South Africa.

STATSSA (Statistics South Africa) (2016c) Community Survey, Media release Mpumalanga community survey http://www.statssa.gov.za/?p=8150 (Accessed 9 September 2021).

STATSSA (Statistics South Africa) (2019) *Inequality Trends in South Africa: A multidimensional diagnostic of inequality*. StatsSA, Pretoria. https://www.statssa.gov.za/publications/Report-03-10-19/Report-03-10-192017.pdf (Accessed 3 October 2019).

STATSSA (Statistics South Africa) (2020) Census of Commercial Agriculture, 2017 – Mpumalanga: Financial, production and related statistics. 11-02-09 (2017). Pretoria: StatsSA. ISBN 978-0-621-48291-1.

STATSSA (Statistics South Africa) (2021a) Statistics by place – Mbombela. http://www.statssa.gov.za/?page_id=993andid=mbombela-municipality (Accessed 12 January 2021).

STATSSA (Statistics South Africa) (2021b) Consumer price Index. Statistical Release, P0141. http://www.statssa.gov.za/publications/P0141/P0141March2021.pdf. (Accessed February 2022).

STIRLING A (2007) "Opening up" and "closing down": Power, participation, and pluralism in the social appraisal of technology. Science Technology and Human Values **33** 262-294. doi:10.1177/0162243907311265.

SUŠNIK J, CHEW C, DOMINGO X, MEREU S, TRABUCCO A, EVANS B, VAMVAKERIDOU-LYROUDIA L, SAVIĆ DA, LASPIDOU C and BROUWER F (2018) Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The SIM4NEXUS approach. Water **10** 139. https://doi.org/10.3390/w10020139.

SUTTON J and AUSTIN Z (2015) Qualitative Research: Data collection, analysis, and management. Canadian Journal Hospital Pharmacy **68(3)** 227-231. doi: 10.4212/cjhp.v68i3.1456.

TAGUTA C, DIRWAI TL, SENZANJE A, SIKKA A and MABHAUDHI T (2022) Sustainable irrigation technologies: A water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare. Environmental Research Letters **17(7)** 073003. doi: 10.1088/1748-9326/ac7b39.

TETT G (2015) *The Silo Effect: The Peril of Expertise and the Promise of Breaking Down Barriers,* Simon and Shuster, New York, NY.

TPTC (Tripartite Permanent Technical Committee) (2002) Tripartite interim agreement between the Republic of Mozambique and the Republic of South Africa and the Kingdom of Swaziland for co-operation on the protection and sustainable utilisation of the water resources of the Incomati and Maputo watercourses. Resolution of the Tripartite Permanent Technical Committee on exchange of information and water quality. TPTC, 29 August 2002, Johannesburg, South Africa.

UNDG (United Nations Development Group) (2016) Sustainable Development Goals Acceleration Toolkit. https://undg.org/2030-agenda/sdg-acceleration-toolkit.

VAN DER LAAN M, VAN ANTWERPEN R and BRISTOW KL (2012) River water quality in the northern sugarcane-producing regions of South Africa and implications for irrigation: A scoping study. Water SA **38(1)** 87-96. doi: 10.4314/wsa.v38i1.11.

VAN DER LAAN M, JUMMAN A and PERRET SR (2015) Environmental benefits of improved water and nitrogen management in irrigated sugar cane: A combined crop modelling and life cycle assessment approach. Irrigation and Drainage **64** 241-252. doi: 10.1002/ird.1900.

VAN LEYNSEELE Y and OLOFSSON M (2023) Unpacking land-associated assemblages 'from below': Smallholders' land access strategies at the commercial tree-crop frontier. *Political Geography*, **100** 102792. https://doi.org/10.1016/j.polgeo.2022.102792.

VAN WYK A (2018) Earning you almost R375 00 per hectare, this must be SA's most valuable crop. https://www.news24.com/news24/bi-archive/sas-most-profitable-crop-2018-3. (Accessed 26 April 2023).

VOLKERY A, RIBEIRO T, HENRICHS T and HOOGEVEEN Y (2008) Your vision or my model? Lessons from participatory land use scenario development on a European scale. Systematic Practice and Action Research **21** 459-477. doi:10.1007/s11213-008-9104-x.

WAKEEL M, CHEN B, HAYAT T, ALSAEDI A and AHMAD B (2016) Energy consumption for water use cycles in different countries: A review. Applied Energy **178** 868-885. https://doi.org/10.1016/j.apenergy.2016.06.114.

WATER IN THE WEST (2013) Water and energy nexus: A literature review. Stanford Woods Institute for the Environment, and The Bill Lane Center for the American West, Stanford University, California, USA. https://waterinthewest.stanford.edu/resources/publications-directory/water-and-energy-nexus-literature-review

ZAREI S, BOZORG-HADDAD O and SINGH VP (2021) Developing water, energy, and food sustainability performance indicators for agricultural systems. Scientific Reports **11** 22831. doi.org/10.1038/s41598-021-02147-9.

ZHANG C, CHEN X, LI Y, DING W and FU G (2018) Water-energy-food nexus: Concepts, questions and methodologies. Journal Cleaner Production **195** 625-639. https://doi.org/10.1016/j.jclepro.2018.05.194.

ZHANG P, XU Z, FAN W, REN J, LIU R and DONG X (2019a) Structure dynamics and risk assessment of water-energy-food nexus: A water footprint approach. Journal Sustainability **11** 1187-1205. https://doi.org/10.3390/su11041187.

ZHANG P, ZHANG L, CHANG Y, XU M, HAO Y, LIANG S, LIU S, YANG Z and WANG C (2019b) Food-energy-water (FEW) nexus for urban sustainability: A comprehensive review. Resources, Conservation and Recycling **142** 215-224. doi.org/10.1016/j.resconrec.2018.11.018.

APPENDICES

APPENDIX 1: QUESTIONNAIRES

APPENDIX 1.1 SEMI-STRUCTURED INTERVIEW INSTRUMENT

Water energy food (WEF) nexus as a framework for catchment-based assessments: the case of the Inkomati-Usuthu Catchment Area

PURPOSE OF THE STUDY

This research investigates how various decisions are made in terms of the use, distribution and/or development of water, and energy food. Specifically, it explores the decisions that YOU have had to make in this regard in the Inkomati-Usuthu Catchment Management area. The study will apply a Water-Energy-Food (WEF) nexus model/framework at a catchment level for the Inkomati-Usuthu Catchment in Mpumalanga and will develop a process to guide real decision-making. The research will make use of different stakeholder engagement methods such as stakeholder meetings, semi-structured interviews, focus group discussions and workshops. The outputs of this project are expected to provide integrated solutions that support decision-making of the complex relationships among sectors, water management and distribution throughout the lnkomati-Usutu catchment. Therefore, overall, it will improve the livelihoods of all communities in lnkomati-Usutu catchment by creating awareness and consciousness about the integrated way in which we need to think about water, energy and food.

Meta-data

Province	
District / Local Municipality	
Institution	
Division	
Contact Phone Numbers	**Tel:**
	Cell:
	Email:
Date of interview	
Name of interviewer	

Industry	✓	**Tick the most appropriate**	✓
Agriculture		Water	
Municipal		Mining	
Mining		Tourism	
Forestry		Other **(specify)**	
Energy			

	Decision making
1.	What key decisions are made in the catchment when it comes to development planning (food, water, energy, forestry, mining, etc.)? How are you involved in these decisions?
2.	Is there cross-sector / industry collaboration during decision making, please elaborate. What are the biggest bottlenecks to cross-sector / industry collaboration? What are some success stories of cross-sector collaboration?
3.	How do you maintain regular communication with stakeholders, e.g. provide regular updates on the implementation of projects and implementation of key decisions?
4.	What are the key drivers that determine / affect decision-making? Please can you give some examples?
5.	Identify the inter-sectoral policy issues and rivalries (e.g. up-stream down-stream tensions, governance and decision making tensions in the forum / catchment)
6.	What are the main benefits of cooperation / association in the basin?
7.	How can the water-energy-food security be improved in your area?
8.	How can policy coherence be enhanced for effective policy implementation?
9.	How can the achievement of long-term sustainability be achieved while maintaining the trade-offs between water, energy and food?

10.	Which do you think are the key drivers that will lead the technological and social research roadmaps for the future in the Water-Energy, Food-Water and Energy-Food nexus?
11.	Do you think all of the nexus (Water-Energy, Food-Water & Energy-Food) have the same importance or is there any one nexus that in your opinion should be prioritized? Justify your answer.

The below questions use the five-point Likert scale ranging from "strongly disagree" to "strongly agree".

12. To what extent to do you agree or disagree with the below statement	**1= strongly agree**	**2 = agree**	**3 = neutral**	**4 = disagree**	**5 = strongly disagree**
12.1 Operation of reservoirs, hydropower and water diversions have limited the availability for downstream water					
12.2. Water shortages are expected in the future					
12.3. There have been agriculture-induced water shortages					
12.4. There have been industrial-induced water shortages					
12.5. There have been municipal-induced water shortages					
12.6. Water availability has been an issue in the basin					
12.7. Key water decisions are made in isolation					

13. To what extent to do you agree or disagree with the below statement	**1 = strongly agree**	**2 = agree**	**3 = neutral**	**4 = disagree**	**5 = strongly disagree**
13.1. Experts and stakeholders are engaged adequately to address policy-needs					
13.2. Stakeholder feedback is often sought to ensure that information is locally relevant, meaningful, and understandable.					
13.3. Stakeholders' concerns are addressed to inform nexus decision-making,					
13.4. A diverse group of stakeholders in knowledge production is engaged for decision making					
13.5. During decision-making, development and climate change scenarios are considered					
13.6. Key development priorities are politically motivated					

14. In your perception, to what extent do you agree with the following statements?	**1= strongly agree**	**2 = agree**	**3 = neutral**	**4 = disagree**	**5 = strongly disagree**
14.1. Agricultural products and waste can serve as sustainable energy sources.					
14.2. Increased agricultural activity (irrigation, fertilizer, machinery) is energy intensive.					
14.3. Increased agricultural production (irrigation) requires increased water-use efficiency.					
14.4. Increased agricultural activity (fertilizers, pesticides) influences water quality.					
14.5. Increased water supply requires increased energy for pumping and treatment.					
14.6. Energy production (hydropower, cooling) influences water-related ecosystems.					
14.7. Sustainable agriculture influences water management practices.					

The below questions use the four-point Likert scale ranging from 1 being the "least important" to 4 being "most important"

15. Would you consider the list below to be least important or most important in the WEF nexus in your area?	**1**	**2**	**3**	**4**
High efficiency – low water consuming cooling systems				
Hydro-wind energy integration				
New generation biofuels				
Hydraulic pumping Energy storage (as key for renewables take off)				
Alternative fluids for drilling and as heat exchange vectors				
Evaporation control				
Integrated water-energy modelling				
Self-generation, (e.g. solar or wind) e.g. solar pumping				
Other (specify)				
Other (specify)				
Other (specify)				

General comments:

APPENDIX 1.2 FOCUS GROUP DISCUSSION GUIDE

Theme 1: General factors influencing decision-making.

This was an interactive exercise where participants were expected to write down their responses using google slides or mentimeter.

1. What are the main factors influencing decision-making processes (planning) in your job? (Word cloud)
2. Now let's rank these factors (1 being the most important influence; x being the least important influence)
3. What are the main factors influencing policy implementation in your job? (word cloud)
4. Now let's rank these factors (1 being the most important influence; x being the least important influence).

Theme 2: Understanding of the WEF nexus and its relevance to decision-making

This was an interactive exercise where participants were writing down a definition of the WEF nexus and whether it helps them in their day-to-day decision-making, planning, design and implementation duties.

5. What does the WEF nexus mean to you?
6. How useful is it in supporting/informing your day-to-day decision-making, planning, design and implementation duties?

Theme 3: Discussion of specific policies and data applicable to an integrated WEF nexus lens/approach

7. Which policies/strategies/plans/regulations that you have developed/used/apply in your job, require an integrated consideration of water, energy and food? Please be as specific as possible listing specific policies that you work with.
8. What about them requires an integrated WEF nexus approach? How is the integration achieved?
9. What metric/data and data sources do you use to inform these decisions? Try to be as specific as possible (specific data and source).
10. How accessible/available is this data? How easy/difficult is it to find/update data to inform your policy-making processes?
11. How much say do you have in determining what data is used?
12. To what degree does evidence (metrics, data) shape your policy-making process?

Theme 4: Challenges to effective integrated WEF decision-making (planning, design and implementation)

13. What would you say are the major challenges to effective integrated WEF decision-making? Let's look first at the planning process and how policy is designed; then let's look at the implementation process.
14. We understand that for many decision-makers, particularly in government, coordination across departments, across government tiers is a major challenge. Is this an issue for you? And how?

APPENDIX 1.3 SCIENCE COMMUNICATION RESEARCH QUESTIONNAIRE

Research Title: Application of science communication methods to facilitate the process of stakeholder engagement, Inkomati-Usuthu Catchment in Mpumalanga, South Africa.: a case study of the crocodile catchment.

Dear participant

These semi-structured questions are designed for the Water Research Commission Project aimed at a research project intended at investigating the Water energy food (WEF) nexus as a framework for catchment-based assessments: the case of the Inkomati-Usuthu Catchment

Confidentiality

Any data and information collected in this questionnaire will be treated with strict confidentiality and will not be exposed to any third parties. Also note that this questionnaire is done anonymously, so personal details will be collected in the process, except for follow-ups should there be any.

For clarity, please contact:

1. Researcher: Sylvia Machimana (Master's student at the University of the Western Cape)
   Contact details: 086 138 5108/ sylviam@iucma.co.za
2. Supervisor: Dr Thokozane Kanyerere (Senior lecturer at the University of the Western Cape)
   Contact details: 021 959 9292/ 071 903 1722 / tkanyerere@uwc.ac.za
3. WRC WEF Nexus Project Coordinator: Professor Sue Walker (Principal Researcher: Agrometeorology at Agricultural Research Council of South Africa)
   Contact Details: 012 310 2577/ 082 806 4858/ walkers@arc.agric.za

Questions

1) Which of the following stakeholder groups do you associate with?

   a) Agriculture
   b) Energy
   c) Water
   d) Media
   e) Policy
   f) Science
   g) Business and industry
   h) Other, please specify:

2) On which level do you generally operate? (*Multiple answers possible*)

   a) Local
   b) National
   c) regional
   d) international

3) Are you aware of the concept of science communication?

   a) Yes
   b) No

   If yes, what is your understanding of science communication?

   ____

   ____

   ____

   ____

   ____

   ____

4) At what stage of this project were you involved? (Multiple answers possible)

a) development of the project plan
b) data collection
c) data analysis
d) interpretation of results
e) dissemination of results
f) other, please specify:

5) How would you best be involved in a research project? (Multiple answers possible)

a) Regular updates about the project (e.g. through a newsletter or email)
b) Meetings
c) Regular workshops
d) Digital/ Visual tools, e.g. videos, posters, diagrams
e) Personal dialogues with project individuals
f) Participating in fieldwork

Please motivate for your answer:

____

6) Which barriers do you think hinder effective participation in communicating scientific research projects? (Multiple answers possible)

a) Time constraints
b) Personnel limitations (e.g. language/ jargon)
c) Financial limitations
d) Organisational restrictions
e) If other, please specify:

Please motivate for your answer:

____
____
____
____
____

7) would you like to propose how similar projects can be communicated in future?

a) Yes
b) No

Please motivate for your answer:

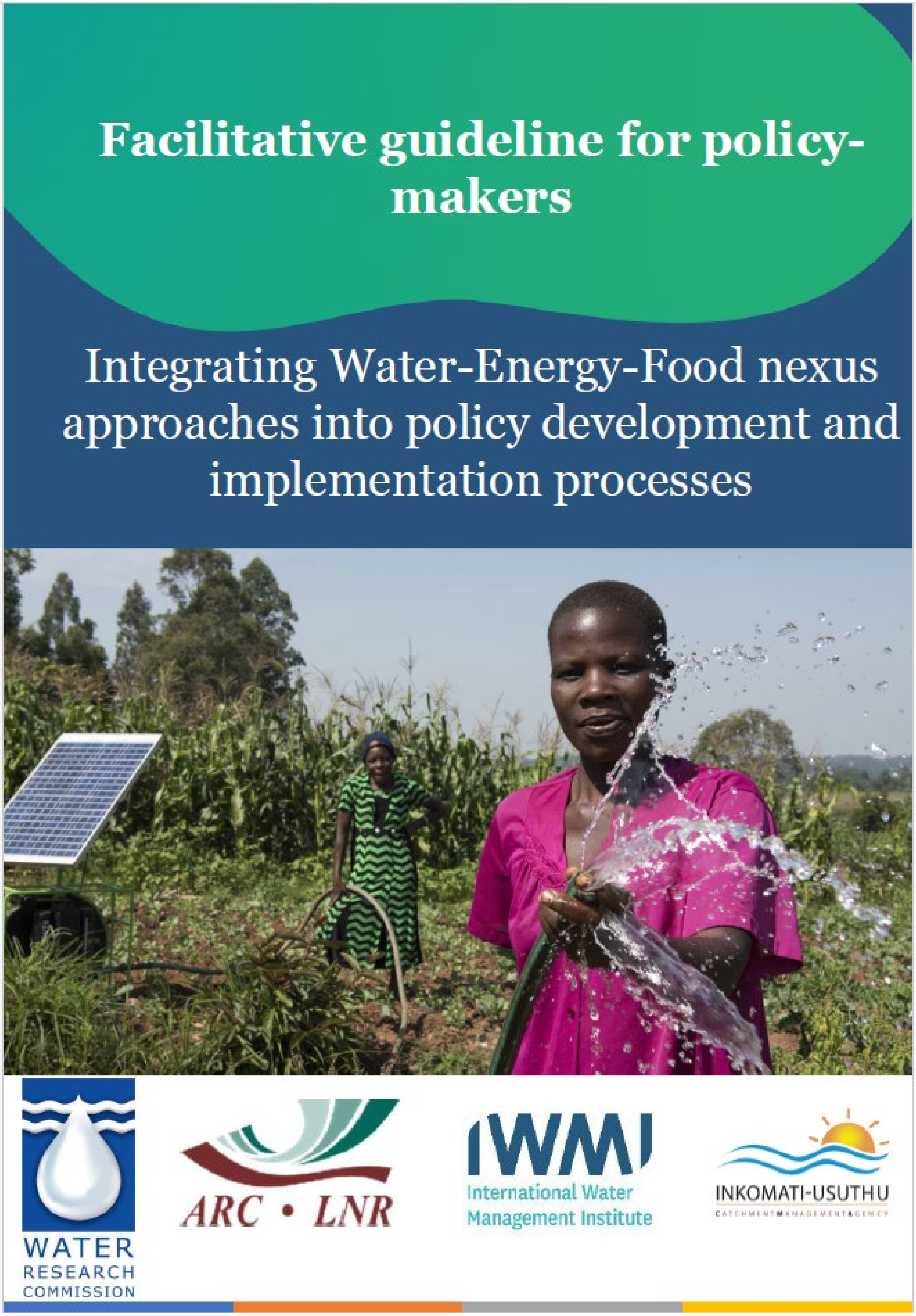
____
____
____
____
____

Thank you for participating in this questionnaire.

Please indicate if you would be interested in taking part in similar projects in future. Tick/cross the applicable answer:	Yes	No

APPENDIX 2: FACILITATIVE GUIDELINE ON STAKEHOLDER ENGAGEMENT

To be published as a separate document by the WRC.



APPENDIX 3: POLICY BRIEF

Exploring the Water-Energy-Food Nexus in the Crocodile Catchment

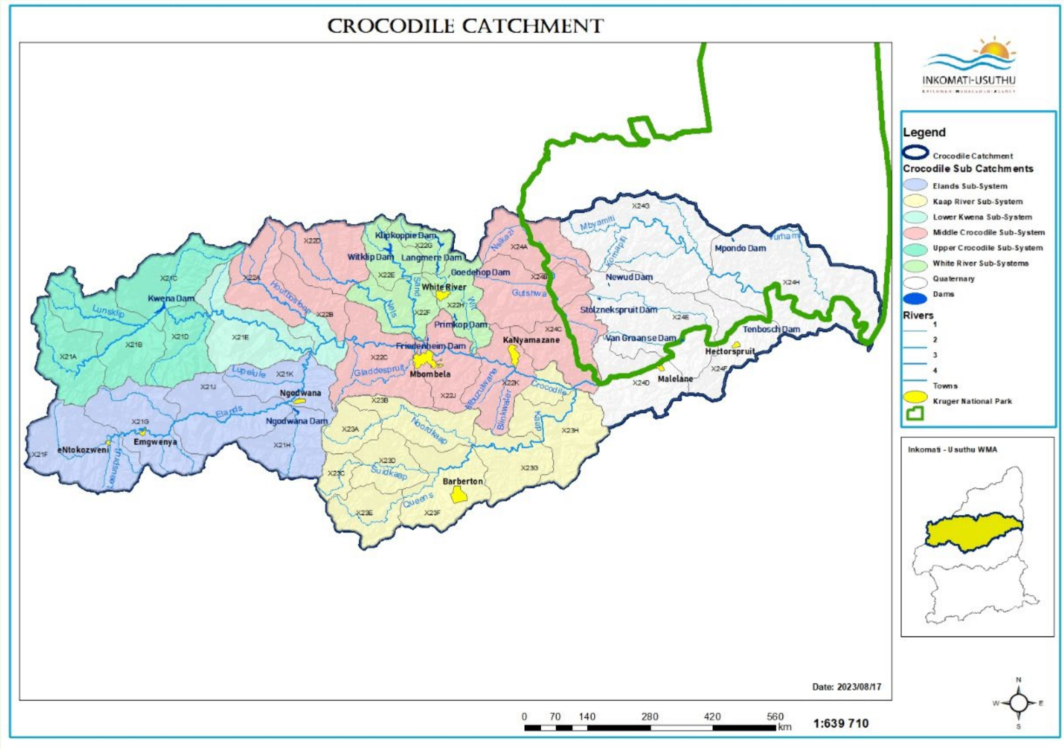
The Crocodile River (East) catchment in Mpumalanga has a vitally important role in the province's food production and energy generation, supplying vast amounts of water for irrigation and coal-fired power stations. Its water resources are also in growing demand from urban areas to support domestic and industrial requirements, while the river itself has great biodiversity value, having a broad range of habitats and forming the southern boundary of the Kruger National Park.

A project funded by the Water Research Commission and conducted by the Agricultural Research Council (ARC) and the International Water Management Institute (IWMI), in partnership with the Inkomati-Usuthu Catchment Management Agency (IUCMA), applied the water-energy-food nexus approach to guide decision-makers in managing the competing needs within the catchment.

Background

South Africa's National Development Plan proposes increasing agricultural development by expanding the land area under irrigation and productive management to reduce poverty and unemployment in rural areas. It also aims to ensure household food security and increased access to electricity and safe water supplies.

Achieving these targets will inevitably create conflicting demands on resources, which needs to be understood to ensure that development is both sustainable and resilient to the impacts of climate change. Numerous models, tools and frameworks have been developed internationally to analyse the relationships, synergies and trade-offs in the water, energy and food sectors. These have been applied at a variety of spatial and time scales, with outputs used for specific purposes ranging from day-to-day management decisions to long-term strategic planning. In southern Africa, the WEF approach has to date been mainly applied at the national and regional levels.



Map of the Crocodile catchment area (Source: IUCMA, 2023)

The Crocodile River catchment forms part of the Inkomati-Usuthu Water Management Area (WMA), which is situated in Mpumalanga province, South Africa. The Crocodile River rises in the mountains near Dullstroom and flows into the Kwena Dam before continuing eastwards through the City of Mbombela. It then forms the southern boundary of the Kruger National Park and merges with the Komati River at Komatipoort, near the Mozambique border.

The Elands and Kaap Rivers are the two main tributaries, and there are a number of smaller dams in the catchment. The main water use is agricultural irrigation, followed by energy production by coal-fired power stations. However, the demand from the municipal sector to support domestic and industrial needs is increasing. The allocation of water is managed by the Inkomati-Usuthu Catchment Management Agency (IUCMA), which convenes quarterly catchment management forums to facilitate engagement with farmers, water irrigation boards and other stakeholders in an effort to ensure the allocation is equitable.

WEF nexus analyses

A review of tools and frameworks available for WEF nexus analyses was conducted, and a few were selected as suitable for application in the Crocodile River catchment. The Analytical Livelihoods Framework and Sustainability Performance Indicators were used to identify pertinent WEF indicators, but since it was not possible to obtain all data at the catchment level, most indices were calculated for the provincial (Mpumalanga) and municipal (City of Mbombela) level.

Three indices were then selected for each of the WEF sectors (**Table 1**) for depiction in a spider chart (**Figure 1**) to reveal the relative strengths and weaknesses in each sector. Such a graph can be used to identify areas requiring intervention and to evaluate synergies and trade-offs in resource planning and utilisation.

Table 1: Sustainability Performance Indicators (SPIs) used to illustrate the WEF linkages within the Crocodile River Catchment.

WEF Sector	Indicator	Score
Water	Water Stress *(available water supply : total demand in catchment = 87%)*	0.87
	Households with water access *(91% of households in Mpumalanga province [MP])*	0.91
	Water Efficiency Index *(crop water requirement : irrigation water + rainfall = 83%)*	0.83
Energy	Population with electricity access *(87.8% in MP in 2015, 91% in Mbombela in 2016)*	0.90
	GHG emission for energy use *(~55% of greenhouse gas emission per farm)*	0.55
	% provincial energy consumption used in sugar industry *(estimated at 38%)*	0.38
Food	Food Insecurity index *(27% of MP population has less than adequate food supply)*	0.27
	Cultivated land index *(19% of MP land area is used for food production)*	0.19
	Consumer Price Index *(2019 CPI in MP had risen 18% since base year 2016)*	0.18

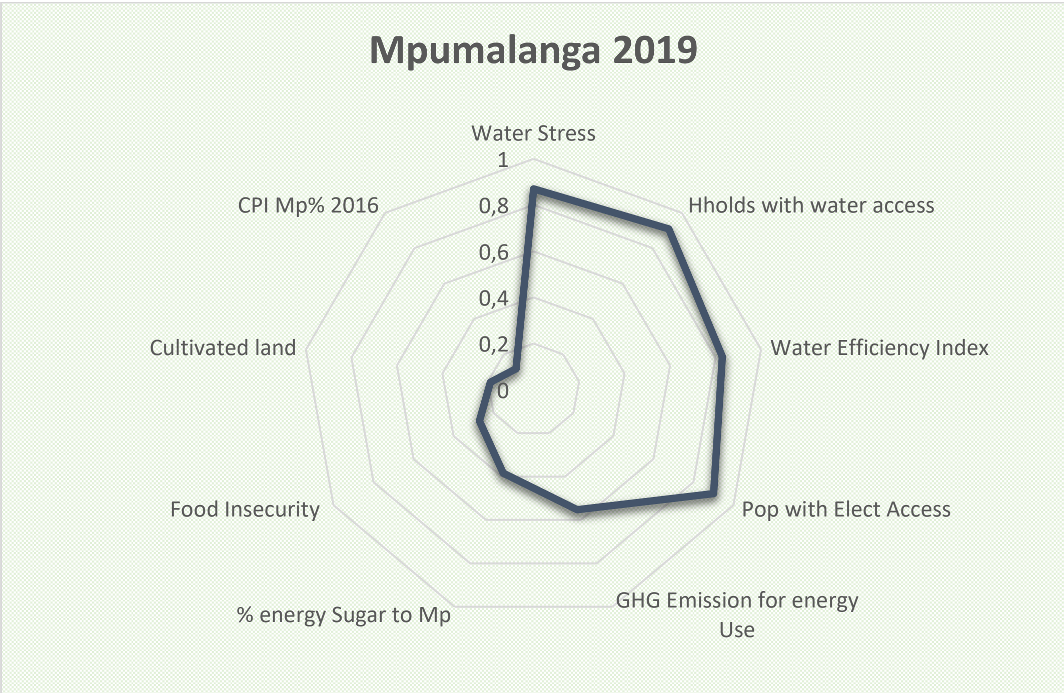


Figure 1: Spider chart of WEF nexus indices for the Crocodile River catchment, using data obtained from a variety of sources for Mpumalanga and the Mbombela municipal area, for the period 2014-2019.

A Life Cycle Assessment (LCA) approach, which allows environmental impacts to be assessed, was used together with WEF indicators to compare sugarcane and macadamia crops. Sugarcane is dominant in the lower reaches of the Crocodile River catchment, while macadamia orchards are increasingly replacing commercial forestry plantations and sugarcane fields in the area. The assessment included the calculation of water footprints (water use impact from 'cradle to grave'), water use efficiency (crop yield: water consumption) and energy productivity (crop yield: irrigation energy input).

The results were then incorporated into a case study comparing scenarios being considered by IUCMA to address current and projected water shortages. The scenarios were:

- Develop the resource – build the Mountain View Dam on the Kaap River
- Switch to crops with lower water requirements – from sugarcane to macadamias
- Switch to a more efficient irrigation system – from centre pivot to drip irrigation
- Switch to a more efficient irrigation system and crop – to macadamia with drip irrigation.

Data was collated for each of these scenarios and WEF nexus indicators were derived to compare water available for domestic consumption and irrigation; the energy saving affecting the amount of energy use versus availability and the cost of electricity infrastructure; and the production of food and nutrients, given that nuts are more nutritious than sugar-based foods. In addition, environmental impacts were considered by including the effect on biodiversity and the river flow regime.

These indicators were depicted in a spider chart (**Figure 2**), which reveals that the development of the Mountain View Dam would have the greatest benefit in terms of water supply for both domestic consumption and irrigation, but the largest impact on biodiversity and river flows. Converting sugarcane production to drip irrigation would save both water and energy compared to the existing pivot irrigation. Macadamia is a more water-efficient crop and can be grown under rainfed conditions, drip irrigation or micro-spray irrigation, so switching to macadamia production would increase water availability for other purposes and reduce the disruption of river flows. Installing electricity infrastructure for drip irrigation of orchards would require a high initial outlay, but operational costs would be lower than pivot systems in sugarcane, with costs that are too high for emerging farmers unless externally funded. Macadamia also scored the highest values for food and nutrient production, although it was recognised that nuts are too expensive for much of South Africa's population to consume.

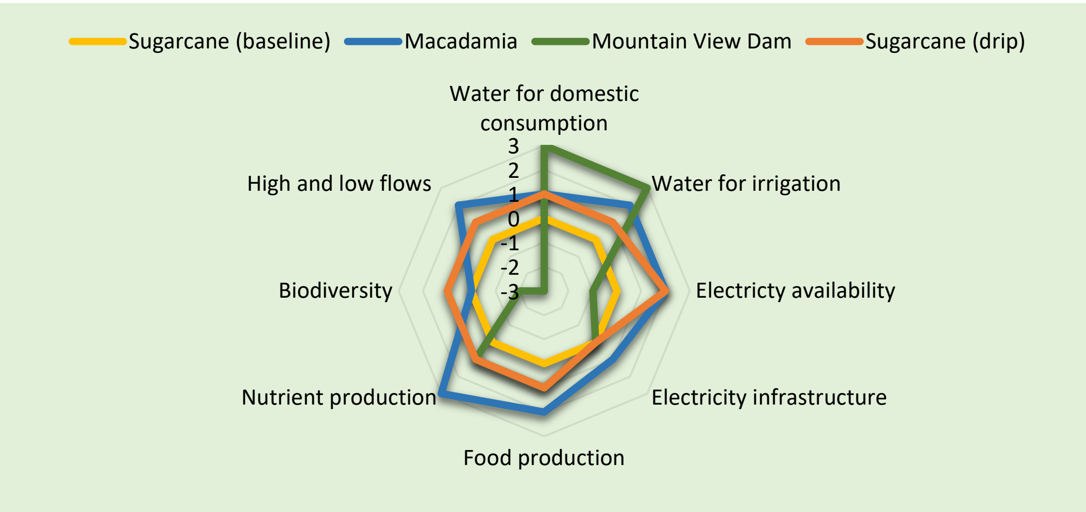


Figure 2: Spider chart of WEF nexus indices to compare scenarios for improving water resources in the Crocodile River Catchment.

Stakeholder engagement

The project included considerable stakeholder engagement, both to collect information and to raise awareness about the WEF nexus approach. Although much of the data used in the analyses was sourced from IUCMA databases and Statistics South Africa publications, additional data relating to sugarcane and macadamia was obtained from private and public organisations in the agricultural sector.

The research team presented the project at existing communication platforms such as catchment management forums, provincial climate change forums, and the research and development committee of the Mpumalanga government. Semi-structured interviews and questionnaires were used to identify other stakeholders, and in November 2020 a stakeholder workshop was convened where a Participatory Scenario Development (PSD) process was conducted. This involved the development of sector-specific visions for the year 2050 for the urban, industry, agriculture, water and environment sectors, followed by deliberation of their feasibility under four scenarios that emerged during the discussions, namely:

- **Scenario 1** *Adapt and Thrive – Agriculture in the Climate Crisis of 2035* (characterised by climate change, i.e. hotter, drier, floods)
- **Scenario 2** *The Emergent Era – A Socio-Economically Transformed 2050* or The Global Market Frontier of 2050 (characterised by socio-economic change, i.e. global competition, inequality, sustainable access, industry support)
- **Scenario 3** *The Governance Imbalance of 2050 – The Fractured Nexus* (characterised by political/policy change, i.e. a lack of commitment from the government, and change in political power)
- **Scenario 4** *The Stagnant Nexus of 2050 or Unchecked Trajectory – The Depletion of the Water-Energy-Food Nexus in 2050* (characterised by business-as-usual management of the WEF nexus)

Two Focus Group Discussions were subsequently held with key staff from IUCMA and the City of Mbombela, respectively, to discuss themes that emerged through the PSD process. Towards the end of the project, a validation workshop was held in November 2022 with participants from IUCMA, water boards, provincial departments and developmental partners, where the scenarios developed through the PSD process were reviewed and adjusted according to expert knowledge.

These qualitative approaches to data collection highlighted the importance of participatory stakeholder engagement in WEF nexus decision-making. However, there is a lack of feedback loops and community validation of information gathered through participatory processes in the Crocodile catchment, where WEF-related decision-making is also influenced by politics, stakeholder priorities, strategic policy priorities, and competing demands among sectors, stakeholders and government departments.

Sectoral coordination is crucial if the WEF nexus concept is to have a meaningful impact on stakeholder decision-making and be implemented for practical applications that ensure holistic and equitable management of resources. Yet coordination is being hindered by the constraints faced by government stakeholders, such as limited budgets and human resource capacity, and currently, there is minimal coordination even within sectors. Improved coordination could be achieved through cooperation, coercion and competition, but it is also important that the decision-making process is not unnecessarily delayed by trying to accommodate the diverse interests of stakeholders.

Central to future WEF nexus framework development are the four principles of enhancing understandability, ensuring reliable and valid data, adaptability to diverse situations, and applicability across scales. These principles will be instrumental in increasing the benefits and improving the role of the WEF nexus concept in influencing policy and resource planning processes.

Research implications

The study findings indicated that converting some cultivated land in the Crocodile River catchment to macadamia orchards would be warranted, based on benefits in terms of water, energy and food efficiency. The export earnings derived from this high-value crop could assist the broader economy, potentially leading to indirect gains for food security. However, given the crop's intensive post-harvesting requirements and the expense of establishing orchards, macadamia is not an ideal option for small-scale farmers. The trees typically take at least five years to bear fruit and the maximum yield is at about 10 years, although vegetables, cover crops and other crops can be planted between them to generate income in the interim. Theft and plant pests are major challenges to macadamia farmers, while climate change presents an additional threat, as a predicted increase in rainfall intensity may reduce nut quality and promote plant diseases.

Even where cultivated land is not converted to macadamia, it will be important to switch to more water-efficient crops and/or irrigation systems. Following the updated reconciliation strategy study for the Mbombela municipal area (DWS 2021), the Mountain View Dam was one of four dams selected for further investigation, and a Pre-feasibility Study to confirm the most appropriate dam site for a more detailed study is underway. The dam would be used to supply Mbombela, reducing pressure on the Kwena Dam, and will also provide releases downstream for irrigation, environmental requirements and international obligations.

Other options being implemented or considered by IUCMA to improve water security in the Crocodile River catchment include reducing domestic water demand, replacing irrigation canals with pipelines, removing alien invasive plants, and reducing afforestation and pollution, which is on the rise due to urbanisation. Reallocation of water resources using the compulsory licence process is considered a last resort.

Conclusions and recommendations

The project demonstrated how the WEF nexus approach could potentially be used by catchment management authorities in their decision-making at a strategic and operational level, although more work is needed before it can be used for routine water allocation in the Crocodile River catchment. Challenges related to data availability, governance and resource limitations must be overcome.

Several recommendations related to the application of the WEF nexus approach at the sub-national level are made in the project report. These include, among others, strengthening stakeholder engagement, developing context-specific policy frameworks, enhancing data collection and sharing, building capacity for WEF nexus analysis, fostering collaboration and learning networks, and promoting sustainable and resilient practices.

Locally based WEF management teams should help ensure that WEF resources are managed holistically and equitably, and a series of workshops should be convened to assist decision-makers in applying WEF nexus principles. A detailed economic assessment of the crop change proposed in the project is highly recommended, and other strategic scenarios in the long-term development plan for the Crocodile catchment should be put to the WEF nexus indicators test.

Similar exercises should be conducted in other catchments to address conflicts and develop trade-offs, ensuring that limited water resources can be used productively. However, given the difficulties in obtaining catchment-specific data, it is recommended that WEF nexus indicators are calculated at the district municipality level instead. The project deliverable, *Facilitative Guideline for Policymakers to integrate WEF nexus thinking into policy development and implementation processes*, can be used as the basis for such studies in other important catchments, and could also assist in the establishment of catchment management agencies.

APPENDIX 4: ABSTRACTS OF PUBLICATIONS AND PRESENTATIONS

APPENDIX 4.1 PAPERS PRESENTED AT ICID 2023 CONGRESS OCTOBER 2022, AUSTRALIA

24th ICID Congress & 73rd IEC Meeting
October 2022, Adeliade, Australia

WS-WFE_N
Paper No. 07

CATCHMENT BASED WATER-ENERGY-FOOD NEXUS ASSESSMENT: EXAMPLE OF THE CROCODILE RIVER CATCHMENT, MPUMALANGA, SOUTH AFRICA

Sue Walker[1,4], Inga Jacobs-Mata[2], Nwabisa Masekwana[1,5], Bhekiwe Fakudze[2,5] and Tendai Sawunyama[3]

ABSTRACT

In South Africa there is increasing demand for the scarce water available, particularly from the agriculture, food and energy sectors which creates conflict, so a sustainable method of allocation is needed. The Water - Energy - Food (WEF) nexus approach quantifies water use and assists in understanding the linkages requiring trade-offs while identifying synergies for sustainable development and natural resources management at various temporal and spatial scales. Although there have been regional and country level assessments within the Southern African Development Community, SADC, there are few studies at local scale, such as catchment or municipality level analyses.
The Crocodile River catchment in Mpumalanga serves as a pilot study to apply a detailed procedure of documenting all factors related to water, energy and agriculture in this area. The Inkomati-Usuthu Catchment Management Agency (IUCMA) actively operates a detailed computerised catchment management programme, meaning there should be sufficient water data available to use WEF nexus analysis tools. In addition, data was collected from various sources. Available WEF nexus tools, models and frameworks were reviewed, including an assessmmnet of their primary application at different geographic scales, noting whether software is developed to use in other areas. The selected short list of WEF tools was investigated and run on a historic dataset to establish a baseline.
Stakeholder engagement, using a facilitative methodology, captured and documented their understanding of WEF nexus concepts and trade-offs using workshops, focus groups and surveys. Participatory scenario development was used to develop four scenarios – namely business as usual; climate change; socio-economic change and political and/or policy change, to assist in integration of WEF nexus outputs at different time and spatial scales for diseminatation to stakeholders. The anticipated outcome will be formulated actions to protect vulnerable communities, landscapes and biodiversity from degradation by cohesively integration of complex interrelated resource systems. WEF issues in the Crocodile River catchment will be addressed to provide guidelines to ensure inclusive socio-economic transformation and development.

Keywords: Inkomati-Usutu catchment, WEF, indices, facilitative methodology, scenarios, South Africa.

24th ICID Congress & 73rd IEC Meeting
October 2022, Adelaide, Australia

WS-WFE_N
Paper No. 10

APPLICATION OF WATER-ENERGY-FOOD NEXUS FRAMEWORK TOOLS AT DIFFERENT SCALES: PRELIMINARY ASSESSMENT

Nwabisa Masekwana[1,3], Sue Walker[1,2] and Michael van der Laan[1,3]

ABSTRACT

A Water-Energy-Food (WEF) nexus tool research study was specifically formulated through a combined quantitative modelling process. The framework tools were applied at provincial (Mpumalanga), municipal (Mbombela) and catchment (Crocodile River) scales. The process was conducted through the collection of and documentation of provincial, municipal and catchment-specific data and statistics to analyse WEF components. The purpose was to increase natural resource use efficiencies and inform coherent strategies for sustainable natural resource management, through the calculation of integrated relationships and links between the three resources. The data was compared and refined using current WEF nexus framework approaches including Analytical Livelihoods Framework (ALF), where indices such as availability and access were calculated. Sustainability Performance Indicators (SPI) were integrated into the study and used to calculate stress indicators on resources. These preliminary results and assessments led to the development of suitable WEF nexus framework indices, and will be discussed with stakeholders at provincial, catchment and municipal levels in the near future. A spider diagram, maps and tables were used for the analysis of the interactions and linkages. The provision of water and energy to households by the municipality was efficient. However, water and energy stresses were high at catchment and provincial levels. Food security is high however, sugar is the base crop and is produced for export. Agriculture also did not form the main source of income and cultivated land was limited to commercial farming whereby food in the form of sugar as the main crop is produced for export purposes. Similar more detailed assessments will be made in future.

Keywords: Mpumalanga, Crocodile River catchment, Mbombela, Analytical Livelihoods Framework, Sustainability Performance Indicators

APPENDIX 4.2 PRESENTATION AT SANCID (SOUTH AFRICAN NATIONAL COMMITTEE ON IRRIGATION & DRAINAGE): 22 FEBRUARY 2023

A REVIEW ON THE MACADAMIA AND SUGARCANE CROPS IN RELATION TO WATER-ENERGY-FOOD NEXUS IN MPUMALANGA

NS MASEKWANA[ab], S, WALKER[ac] AND M VAN DER LAAN[ab]

[a] ARC-NRE, Arcadia, Pretoria, South Africa, [b] University of Pretoria, South Africa
[c] University of the Free State, Bloemfontein, South Africa.
masekwanan@arc.agric.za

Agricultural irrigation is the main user of water, and the project aims to quantify resource use and efficiency in the main crops produced in the Mpumalanga province. Macadamia orchards are seen as an alternative to sugarcane in the Lowveld part of the Mpumalanga province. There is a word-of-mouth perception that Macadamias use half the volume of water compared to crops such as sugar cane, with 89% of the farmers switching to the crop. There is a lucrative potential for the crop in the export market and generation of good foreign exchange. As water is a scarce resource, the contribution macadamias can make through the use of water during production needs evaluation. Water-Energy-Food nexus is a tool applied to assess availability, access and use of the mentioned sectorial resources as these have proven to have diverse allocations, needs and demands. This is done in order to curb the unsustainable use of critical resources such as water. he research compared the resource use of the macadamia and sugarcane crops in order to evaluate possible alternatives and trade-offs within the crops according to the WEF nexus framework. Data were collected from literature on macadamia and sugar to formulate data on water productivity (kg/m^{-3}), water footprint (m^3/t^{-1}), and water requirement demands (m^3/ha^{-1}) and total irrigation water per annum (Mm^3) in order to calculate water use efficiency. The amount of cultivated land (ha), crop yield (t/ha^{-1}) and nutritional value (kJ/100g) of each crop were obtained and calculated. Results showed that sugar has a water productivity of over 10 times higher than that of macadamia with values at 0.85 kg/m^{-3} compared to 10.5 kg/m^{-3}, respectively. This results in a water footprint of about 71 m^3/t^{-1} for sugar compared to that of 1.18 m^3/t^{-1} for macadamia nuts. The water requirement demands were 9000 m^3/ha^{-1} per annum for sugar compared to 7 500 m^3/ha^{-1} per annum for macadamia. Irrigation water used is at 5 241 346 Mm^{-3} for sugarcane compared to 199 493 Mm^{-3} for macadamia. Cultivated land for sugarcane is 3 times (61 666ha) and a yield of 90 t/ha^{-1}, compared to (26 599ha), and a yield of 4.9 t/ha^{-1} of macadamia nuts in the Mpumalanga province. The nutritional value of the crops as food is 1619 kJ/100g for sugar with macadamia at 3 080 kJ/100g for nuts in shell. Water is proving to be a scarce resource in most provinces with Mpumalanga included. There is increased pressure on water resource allocation due to high demand. Macadamia is showing strides in water use efficiency as a crop as it is more tolerant to water stress culminating from drought and adverse conditions. The data in this study has shown that macadamias have fewer resource demands, with even better nutritional value than sugarcane. However, limited research especially on electricity use during production is available and needs to be applied to the crop for South African production.