DEVELOPING A WEB-BASED AND GIS-ENABLED WEF NEXUS INTEGRATIVE MODEL

Final Synthesis Report

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Strategic resources such as water, energy, food, and land are under pressure from changes in climate and socioeconomic conditions and silo-based management approaches. This has led to the pursuit of integrated resource management approaches: the water-energy-food (WEF) nexus. The water-energy-food (WEF) nexus approach acknowledges the inextricable links between WEF resources to maximize and minimize their synergies and trade-offs. This has seen it gaining noteworthy attention in the agenda of policy dialogue, development, and research. For example, the Water Research Commission (WRC) of South Africa has prioritized the WEF nexus as one of its focus "lighthouse" research areas. Several WEF nexus research projects are either in progress or have been completed. This short-term project was part of the WRC's goal to promote the WEF nexus research and implementation in South Africa. To bridge the gap between WEF nexus theory and practice, the global aim of this study was to develop a web-based and GIS-enabled integrative WEF nexus analytic model, iWEF. Specifically, the work reviewed state-of-the-art WEF nexus models tools and developed, tested and disseminated a web-based GIS-enabled WEF nexus analytical tool applicable at different scales. Thus, the scope of this work involved (i) reviewing existing WEF nexus tools and their characteristics, including geospatial analytic capabilities in literature, (ii) developing the web-based and GIS-enabled iWEF modelling tool, (iii) testing the iWEF model in case studies at different scales, and (iv) disseminating the iWEF model to potentially interested public users.

The review of WEF nexus tools was conducted systematically by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol on literature from Scopus and Web of Sciences, with a focus on key characteristics such as trends in the development of WEF nexus tools, availability, format, geospatial analytic capabilities, scales of application as well previous application in case studies. The founding operation principles of iWEF were adapted from an MS Excel-based WEF nexus modelling tool which applies the Analytic Hierarchy Process (AHP) multi-criteria decision making (MCDM) approach to establish quantitative relationships among WEF nexus sustainability indicators. As partly guided by findings from the literature review, the user-friendly, web-based and GIS-enabled iWEF model and its modules were developed using the programming and visualization tools Python, Django, PostgreSQL, PostGIS, Visual Studio Code, Git, and Dash-Plotly, in the iterative modified Waterfall software development life-cycle. The integration of Geographic Information System (GIS) in iWEF was achieved through Leaflet and an OpenStreetMap base map for case study areas and visual-spatial mapping of the WEF nexus. The algorithms in iWEF include automatic computation and display of the consistency ratio to ensure consistency and randomness of the pairwise comparison matrix.

The main findings are that WEF resources are spatially distributed and thus better characterised spatially with WEF nexus tools with geospatial analytic capabilities. However,

literature discovered that the majority of existing WEF nexus tools lack geospatial analytic capabilities. To add, most WEF nexus tools are unreachable to interested users, which inhibits the translation of the WEF nexus theory to practice. Some existing WEF nexus tools are restricted in locations and selective of scales and geographic scope of application, potentially limiting their transferability and application. Some available WEF nexus tools are in code format, which can undermine their applicability to users without programming skills. Thus, the literature review is an updated compendium of WEF nexus tools and their characteristics that can guide interested users to identify, select, and suitability of WEF nexus tools to their context. It also informs developers of WEF nexus tools on considerations in either developing new tools or improving the usability of existing tools.

The user-friendly, web-based and GIS-enabled iWEF model developed under this project was deployed online, and the initial version was tested with data from previous case studies on a regional scale (Southern Africa, 2017 data), national scale (South Africa, 2015 data), and local scale (Sakhisizwe Local Municipality, 2018 data). In this regard, the iWEF model successfully reproduced results from the previous case studies, with added advantages of iWEF being web availability and innovations in the automatic computation of consistency ratio for input pairwise judgements, as well as geospatial analytic capabilities for location (delineation) of case study areas and spatial mapping and visualization of the WEF nexus for analysis and comparison.

The web-accessible iWEF model demonstrated the potential to accurately compute and visualize the WEF nexus, assessing resource availability, distribution, use, and management at multiple scales. However, further testing and validation in different contexts and scales are necessary to enable iWEF to become a tool that informs strategies and guidelines on improving resource management/allocation and human wellbeing and livelihoods, especially for poor rural communities. Thus, in collaboration with WRC project C2019/2020-00007, "From Theory to Practice: Developing a Case Study and Guidelines for Water-Energy-Food (WEF) Nexus Implementation in Southern Africa", the iWEF model will be applied in the coming months in two local (catchment and municipal) case studies in South Africa and Zimbabwe. The case studies in Zimbabwe will be Mzingwane Catchment and Umzingwane District Municipality in Matabeleland Province. At the same time, their South African counterparts will be Inkomati-Usuthu Water Management Area (WMA) and Ehlanzeni District Municipality in Mpumalanga Province, respectively.

Future research should focus on applying the iWEF modelling tool in decision- and policy-making, as well as scenario planning for interventions, investments, and infrastructure development at multiple temporal and spatial scales.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF UNITS IN THE REPORT

m^3/capita	Cubic metres per capita
$/$m^3$	The United States of American dollars per cubic metre
MJ/GDP	Mega Joules per dollar of gross domestic product
kg/ha	Kilogrammes per hectare
MW	Mega Watts

ACRONYMS IN THE REPORT

ABM-SWAT	Agent-Based Model - Soil and Water Assessment Tool
AGU	American Geophysical Union
AHP	Analytic Hierarchy Process
AHP-OS	AHP Online System
Amazon S3	Amazon Simple Storage Service
ARC	Agricultural Research Council
AWEFSM	Agricultural Water-Energy-Food Sustainable Management
BFAP	Bureau for Food and Agricultural Policy
BP-DEMATEL-GTCW	Back Propagation neural networks-DEcision Making Trial and Evaluation Laboratory-Game Theory Combination Weight
BRAHEMO	BRAhmaputra HydroEconomic MOdel
CALFEWS	California Food-Energy-Water System
CI	Consistency Index
CLEWs	Climate-, Land-, Energy- and Water-systems
CR	Consistency Ratio
CSS	Centre for Systems Solutions
CTAFS	Centre for Transformative Agriculture and Food Systems
DAFNE	Decision-Analytic Framework to explore the water-energy-food NExus in complex and transboundary water resources systems of fast-growing developing countries
DEA	Department of Environment Affairs
DoHET	Department of Higher Education and Training
DOI	Digital Object Identifier
DWA	Department of Water Affairs
EFW	Energy-Food-Water
EGU	European Geosciences Union
EPA	Environmental Protection Agency
EPAT	Energy Portfolio Assessment Tool
EWF	Energy-Water-Food
EWL	Energy-Water-Land
FAO	Food and Agriculture Organization
FEW	Food-Energy-Water
FPC	Farm Performance Calculator
FWE	Food-Water-Energy
GIS	Geographic Information System
GREAT for FEW	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus
GUI	Graphical User Interface
GWP	Global Water Partnership
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modelling System
IBMR-MY	Indus Basin Model Revised-Multi Year
ICID	International Commission on Irrigation and Drainage
IRENA	International Renewable Energy Agency
ITEEM	Integrated Technology-Environment-Economics Model

IUCMA	Inkomati-Usuthu Catchment Management Authority
IUWMA	Inkomati-Usuthu Water Management Area
iWEF	Integrative Water-Energy-Food (WEF) Nexus Analytical Model
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
K-WEFS	Karawang Water-Energy-Food (WEF) Security
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LCOW	Levelized Cost of Water
LEAP	Long-range Energy Alternatives Planning System
MAGIC	Moving Towards Adaptive Governance in Complexity: Informing Nexus Security
MCDM	Multi-Criteria Decision Making
MIFCP-WEFN	Multi-level Interval Fuzzy Credibility-constrained Programming Water-Energy-Food Nexus
MuSIASEM	Multiple-Scale Integrated Assessments of Societal Metabolism
MS	Microsoft
NeFEW	Nexus of Food, Energy, and Water
NEST	NExus Solutions Tool
NexSym	Nexus Simulation System
NSL	Negotiation Simulation Laboratory
NWSAS	North-Western Sahara Aquifer System
OGC	Open Geospatial Consortium
PCM	Pairwise Comparison Matrix
PICOS	Population, Indicator, Comparison, Outcome and Study design
PRIMA	Platform for Regional Integrated modelling and Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QR	Quick Response
RI	Random Index
RSA	Republic of South Africa
SADC	Southern African Development Community
SD	System Dynamics
SD Calculator	Sustainable Development Calculator
SDG	Sustainable Development Goal
SEWEM	System-wide Economic-Water-Energy Model
SIM4NEXUS	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe
StatsSA	Statistics South Africa
TRBNA	Transboundary River Basins Nexus Approach
UCEC	Urban Circular Economy Calculator
UKZN	University of KwaZulu-Natal
UNECE	United Nations Economic Commission for Europe
WEAP	Water Evaluation and Planning System
WEF	Water-Energy-Food
WEF-e	Water-Energy-Food-everything
WEFO	Water, Energy and Food security nexus Optimization

WEFSiM	Water-Energy-Food (WEF) nexus Simulation Model
WEST	Water Economy Simulation Tool
WFE	Water-Food-Energy
WHAT-IF	Water, Hydropower, Agriculture Tool for Investment and Financing
WMA	Water Management Area
WoS	Web of Science
WRC	Water Research Commission

CHAPTER 1 INTRODUCTION

1.1 Background to the WEF Nexus

Strategic resources such as water, energy, food and land drive economic and social development. However, these resources are degrading and over-exploited due to societal, environmental, technological, economic and demographic changes (Mabhaudhi et al., 2016; SADC, 2016). The near future projections for 2030 predict demand increases of 40% for water and 50% for energy and food (Martinez-Hernandez et al., 2017; Schull et al., 2020). Business as usual scenario for 2050 project increasing demands of 50% for water, 100% for energy, 60% for food, and 20% for agricultural land (Hoff, 2011; FAO, 2014; IRENA, 2015; Tashtoush et al., 2019). The insecurities of and pressures on these key resources are further amplified by the disconnected sectoral policies and country-focused approaches to management, which ignore the resources' interlinkages, coexistence and transboundary nature (IRENA, 2015; Leck et al., 2015). Recognising that previous approaches to integrated resources management were "siloed", such as the water-centric integrated water resources management (IWRM), has led to the pursuit of holistic, integrated approaches to the management of natural resources, including the water-energy-food (WEF) nexus approach (Leck et al., 2015; Schull et al., 2020).

As proposed at the Bonn 2011 Nexus Conference for WEF Security Nexus Solutions for the Green Economy, the WEF nexus inextricably links water, energy and food resources and sectors at different levels and scales (Hoff, 2011; Flammini et al., 2014; IRENA, 2015). The multi-dimensional interlinkages and interconnections between water, energy and food, which can be synergetic, neutral or trade-offs, are illustrated in Figure 1.

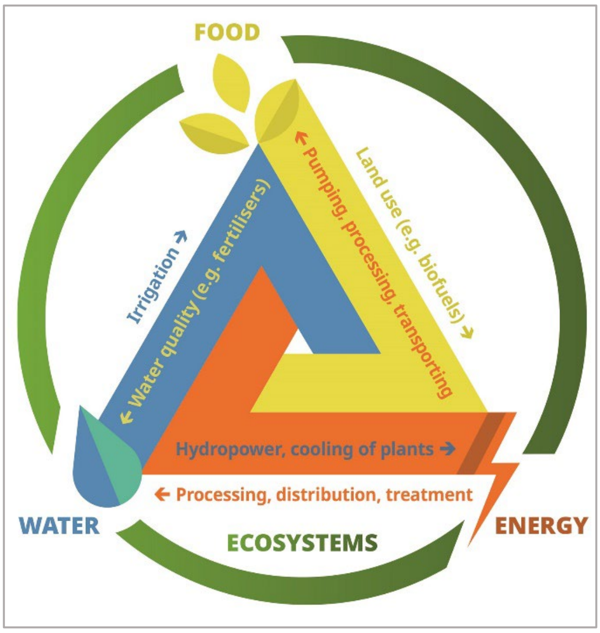

Figure 1: The WEF nexus approach (GWP-Mediterranean, 2020)

Water contributes, at different intensities, to the different energy generation technologies and processes, be it electricity or biofuels. Flowing water energizes turbines in hydropower plants, boiled water (steam) is a source of thermal power, water is a coolant in thermal and nuclear power plants, and water is a key input in the production of biofuels. On the other hand, energy, such as electricity and fuel, is used at different energy intensities to extract, convey, treat, and distribute water to the end-user. Irrigated agriculture consumes about 70% of the global water in food and fibre production, although agricultural products differ individually in their water consumption and footprints (FAO, 2014; Wicaksono et al., 2017). On the other hand, untreated food waste and agricultural return flow with chemical residues from fertilizers and pesticides pollute surface and groundwater, thus compromising water quality and quantity.

Furthermore, some agricultural practices such as accelerated land intensification and farmland expansion tamper with the local hydrology, affecting the water availability and quality. Food production requires energy, by either direct or indirect means. Direct energy includes fuel, electricity and labour, while indirect energy manifests in the form of fertilizer, chemicals and seeds. On the other hand, food contributes to energy by the conversion of agricultural products (e.g. maize/corn, sugar cane, wheat, soybean, jatropha, sorghum, rape seed, food waste) into bioenergy such as biofuel (or bioethanol and biodiesel) and biogas to complement or supplement petroleum, diesel and gas fuel. These examples illustrate the interdependences between WEF resources, some of which are highly competitive (IRENA, 2015; Wicaksono et al., 2017; Wicaksono and Kang, 2019). However, the actual nature, importance and significance of interconnections between the WEF resources are context-specific, and this calls for the implementation of the WEF nexus approach to explore and understand the interdependence of water, energy and food security and the natural resources that underpin their security (Liu et al., 2017; Salam et al., 2017). This translation of the WEF nexus approach theory and concept into practice in policy, governance and infrastructure development is still lagging, possibly due to a lack of supporting evidence and tools that can capture it in its entirety (Leck et al., 2015; Liu et al., 2017; Galaitsi et al., 2018; McGrane et al., 2019).

1.2 WEF Nexus Tools and Models

The multi-centric and multi-dimensional WEF nexus approach is complex to unpack and untangle; it is a relatively new concept (AboeInga et al., 2018) compared to other resource management approaches. Implementing the nexus approach relies on an analysis of cross-sectoral interactions to facilitate integrated planning and decision-making, and this requires the application of quantitative and qualitative decision-support tools and methodologies depending on the motivation of the analysis, access to data and availability of technical capacity (Bazilian et al., 2011; IRENA, 2015). Common existing WEF nexus tools include Water-Energy-Food (WEF) Nexus Tool 2.0 (Daher and Mohtar, 2015), Climate-, Land-, Energy- and Water-systems (CLEWs) (Howells et al., 2013), Multiple-Scale Integrated Assessments of Societal Metabolism (MuSIASEM) (Giampietro et al., 2009), and Water Evaluation and Planning System – Long-Range Energy Alternatives Planning System (WEAP-LEAP) (SEI, 2012).

The Water Research Commission (WRC) recently supported the development of two WEF nexus models, which are the Water-Energy-Food (WEF) Nexus Index developed by Simpson et al. (2022), and the Integrative Analytical model for the WEF nexus by Nhamo et al. (2020a). However, existing WEF nexus computer-based models lack desirable features for advancing the implementation of the WEF nexus, such as feedback analysis, optimization and visualization, availability and geospatial features (Wicaksono et al., 2017). The availability of the tools to the general public users and their geospatial analytic capabilities are still unknown.

1.3 Web-basing and GIS-linking of WEF Nexus Tools and Models

The WEF nexus is a spatially distributed and complex problem that needs an integrative use of information, domain-specific knowledge, and effective communication (Hiloidhari et al., 2017). WEF nexus tools are strong in quantitative and qualitative analysis but weak in dealing with spatial data needed for spatial analysis, mapping, and visualization. The latter is a key strength in GIS systems. On the other hand, GIS is an important decision-making spatial tool that supports the precise assessment of distributed WEF resources, thereby addressing economic and environmental goals (Hiloidhari et al., 2017). GIS is a computer-based information system with tools to collect, store, manipulate, analyse, and visualize spatially defined (geographically referenced) data applicable in natural resources management (Johnson, 2009; Janipella et al., 2019). However, GIS is weak in integrating decision-making and reasoning preferences into problem-solving (Eldrandaly, 2007), a key strength in WEF nexus tools. Thus, GIS and WEF nexus tools are complementary and can be integrated to simultaneously and spatially compute, analyse and map interactions between WEF resources. GIS can be coupled to WEF tools/models in various ways, including 'hard-linked' and 'soft-linked' (Eldrandaly, 2007).

'Hard-linked' or tight (deep) coupling is when one system provides a user interface for viewing and controlling the application built from several component programs between a WEF nexus model and GIS. The superiority of 'hard-linked' integration lies in the effective and automatic exchange of input and output data between the WEF nexus and GIS. This integration is beneficial, easier and convenient for the users because it allows for automatic analysis, mapping and visualization. Still, it demands more competence and effort from developers in coupling (Eldrandaly, 2007). 'Soft-linked' or loose (shallow) coupling between a WEF nexus model and GIS involves the manual data movement between the tool and GIS component. By this approach, GIS serves as a pre-processor or post-processor to the WEF nexus tool; the latter could access the data stored in the GIS or produced by the GIS. It requires less effort to develop new software by the developer, but demands a high level of competence from the user to write data in a shareable format and thus cumbersome and prone to errors (Ramos et al., 2019).

1.4 This Research Project

In April 2021, the project entitled: "Developing a web-based and GIS-enabled WEF nexus integrative model" (WRC C2020/2021-00462) was awarded to the Project Team, based at the School of Engineering, University of KwaZulu-Natal (UKZN) in Pietermaritzburg by the Water Research Commission (WRC). This project is a one-year project with contractual funding of R500 000 over the project cycle from April 2021 to March 2022. Over the one year, a total of 3 deliverables are due to the WRC, which address five (5) specific objectives of the project:

General aim: To develop a web-based GIS embedded WEF nexus analytical tool for the application at different scales.

- Specific objective 1: To conduct a systematic review of WEF nexus applications and tools, which will be used to further refine the proposed methodology in this study.
- Specific objective 2: To develop a GIS-based tool using quantitative and qualitative earth observation data that will be used to assist decision making and policy development for land use and spatial planning.
- Specific objective 3: To test the GIS-based tool at various scales for South Africa.
- Specific objective 4: To facilitate broader dissemination and uptake of the GIS tool.

- Specific objective 5: To compile a generalised policy brief in association with stakeholders and the National Planning Commission (NPC) that will support the transition of energy from mainly fossil fuels to renewables throughout South Africa based on the evidence for the WEF nexus model.

Thus, the intended web-based and GIS-enabled WEF nexus analytical tool (iWEF) will automatically analyse the WEF nexus and produce results in tables, graphs and spatial maps for enhanced geospatial analysis and visualization.

CHAPTER 2 LITERATURE REVIEW

This section presents the methods and findings from systematically reviewing published literature on historic and current trends in developing WEF nexus tools, availability, format, spatial scales of application, geospatial analytic capabilities, and existing WEF nexus tools in previous case studies. This review will update new and old users' WEF nexus tools and provide a starting point for present and future developers who intend to improve existing or create new WEF nexus tools. Secondary to this and without necessarily comparing WEF nexus tools, this review is intended to be a knowledge synthesis to guide and inform interested users of WEF nexus tools on what tools to use under different contexts. This will enhance the quick, easy and effective selection of WEF nexus tools for different conditions and requirements in facilitating the implementation of the WEF nexus approach.

2.1 WEF Nexus Contextualised

Within South Africa, multiple governmental departments are involved in resource planning. The regulatory custodians of water, energy, and food have developed policies and programmes to manage the country's resources sustainably. Yet these departments usually work in silos, which is sometimes reflected in contrasting statements and guideline publications that threaten the sustainable use of resources in the country. The same could be said for provincial regulatory bodies.

For example, the Mpumalanga province has a complex history of water, energy and food security due to it being the powerhouse for coal production in the country since the 1900s as well as an agricultural hotspot for sugarcane, timber, and fruit, both of which have had a direct and continuous impact on the water quality and quantity of the province (BFAP, 2012). Other issues that are shared between the country and its provinces which have a direct impact on sustainable resource management include, but are not limited to, the following:

- lack of implementation of and adherence to resource planning policies and documents,
- illegal activities that result in the deterioration of human- and environmental health,
- policy uncertainty and legislation contradictions,
- ineffectual and inoperative wastewater facilities, and
- lack of investment in and costs associated with renewable energy projects.

The iWEF model developed in this project has the potential to address the following critical research questions, and contextual issues are addressed:

1. What is the historic, current, and predicted future situation of the WEF nexus in Mpumalanga and how does this translate into national planning documents?

2. What are the provincial gaps in research, policy and legislation in terms of integrated resource planning and what opportunities are there for alignment with the WEF nexus framework?
3. How do quantitative and qualitative data collected for provinces compare to the actual WEF nexus situation of the province, and how can this data be used to develop a GIS-based tool to complement policy development and decision making?
4. What are the policy recommendations that originate from using the GIS-based tool in association with the relevant provincial regulatory custodians of water, energy and food?
5. What general policy recommendations arise from the project applicable to South Africa and aligned to the NPC's agenda?

In terms of contribution to the WRC's knowledge tree, the iWEF model will continuously contribute to transformation and redress, sustainable development solutions, empowerment of communities, informing policy and decision making, and human capital development in the Water and Science sectors, and innovation and technology. As a starting point, the GIS-based tool (iWEF) will act as an ancillary assessment and decision-making instrument for forming informed policies and responsible investments for transformational growth.

The WEF nexus tool's analysis of the WEF nexus at different scales will encourage cooperation within and between different departmental sectors in developing integrated policies and decision-making. This is crucial when undertaking site selections for proposed developments to determine the possible impacts on WEF nexus interactions and sustainability.

2.2 WEF Nexus Applications

Before, several detailed and brief literature reviews on the WEF nexus paradigm and its relevant tools were conducted. WEF nexus tools were previously reviewed on several characteristics, including feedback analysis, optimization and visualization (Wicaksono et al., 2017; Wicaksono and Kang, 2019), informing policy (Shannak et al., 2018), as well as entry requirements, exits and analytical capabilities (Rosales-Asensio et al., 2020). Mannan et al. (2018) reviewed analytical features of WEF nexus tools, while Dai et al. (2018) focused on model types, spatial scale, purpose and nexus challenge level. Dargin et al. (2019) delved into the complexity of WEF nexus tools, while Flammini et al. (2014), IRENA (2015), Kaddoura and El Khatib (2017), and Shinde (2017) reviewed their suitability, analytic modelling capabilities, inputs, and outputs. Reviews by Albrecht et al. (2018) and Zhang et al. (2018) included concepts and methodologies in the WEF nexus and tools.

However, significant developments have occurred since these reviews were conducted in the WEF nexus field, rapidly evolving and witnessing the advent of new tools. More tools were developed, and some of the existing ones improved. There is a dire need for an updated review of current WEF nexus tools, status, and potential for GIS integration. Based on this basis and motivation, this current systematic review is founded. This will serve as an update on WEF nexus tools and a starting point for present and future developers who intend to improve existing or create new WEF nexus tools.

2.3 WEF Nexus Models (Tools, Applications), the Web and GIS linkages

To the best of our knowledge, no previous work has reviewed WEF nexus models/tools, focusing on their present status, importance and potential for web accessibility and GIS-enabling. The WEF nexus research landscape is evolving fast such that previous reviews on WEF nexus models/applications/tools are not up to date, and they miss recent developments. This current WEF nexus research work focuses on reviewing the existing WEF nexus applications and tools to provide an essential foundation for interpreting the techniques for developing the web-based and GIS-enabled tool and informing on the quantitative and qualitative data that will be used in the WEF nexus tool. Thus, this review will provide a sound basis for further refining the proposed methodology in developing the WEF nexus tool. In addition, this literature review will enable researchers to address the gaps identified and to further investigate and compare WEF nexus models in space and time. It is also an update of recent and current developments in WEF nexus tools, models and applications. The global aim of this study was to provide a review of the state-of-the-art of WEF nexus tools and their suitability in supporting the implementation of the WEF nexus approach. To fulfil this aim, this study sought to systematically review the available literature and potentially address the following specific objectives to:

i. assess the historic and current trends in the development of WEF nexus tools,
ii. provide an inventory/compendium of existing WEF nexus tools,
iii. review availability, format, spatial scales of application, and geospatial analytic capabilities of existing WEF nexus tools, and
iv. assess the application of existing WEF nexus tools in previous case studies.

2.4 Literature Review Materials and Methods

This study conducted a WEF nexus tools systematic review by mapping broad literature to answer questions regarding characteristics excluded in previous reviews that focused on concepts, methodologies, complexity, and analytical capabilities. These characteristics formed the scope of this study, including development trends, availability, format, spatial scale, geospatial analytic capabilities, and case studies. WEF nexus tools with geospatial capabilities are useful for certain problems but not for all. Thus, there is a need to inform and guide interested users on the status of geospatial analytical capabilities in existing WEF nexus tools. A systematic review seeks to systematically search for, appraise and synthesize research evidence, often adhering to guidelines on the conduct of a review, such as the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Figure 2) (Grant and Booth, 2009; Moher et al., 2009). The PRISMA protocol assists in systematically searching, identifying, and selecting articles on search databases and reviewing them through appraisal and synthesis of research evidence (Grant and Booth, 2009). The PRISMA protocol was updated, further explained and elaborated by Page et al. (2021a,b). The PRISMA protocol can be applied in domains such as natural resources, agriculture and management, as illustrated by Fernandes Torres et al. (2019), who applied the framework in reviewing literature and proposing a systematic procedure of the nexus concept.

The PRISMA flow diagram with results was conveniently generated with the user-friendly open-access R package and ShinyApp for PRISMA Flow Diagram[1] by Haddaway et al. (2021a,b). The PRISMA steps involved, among others, eligibility criteria, information sources, search strategy, screening, selection, data collection, defining data items, and analysis, as further elaborated in the succeeding sections.

[1] https://estech.shinyapps.io/prisma_flowdiagram/; https://doi.org/10.5281/zenodo.5082518

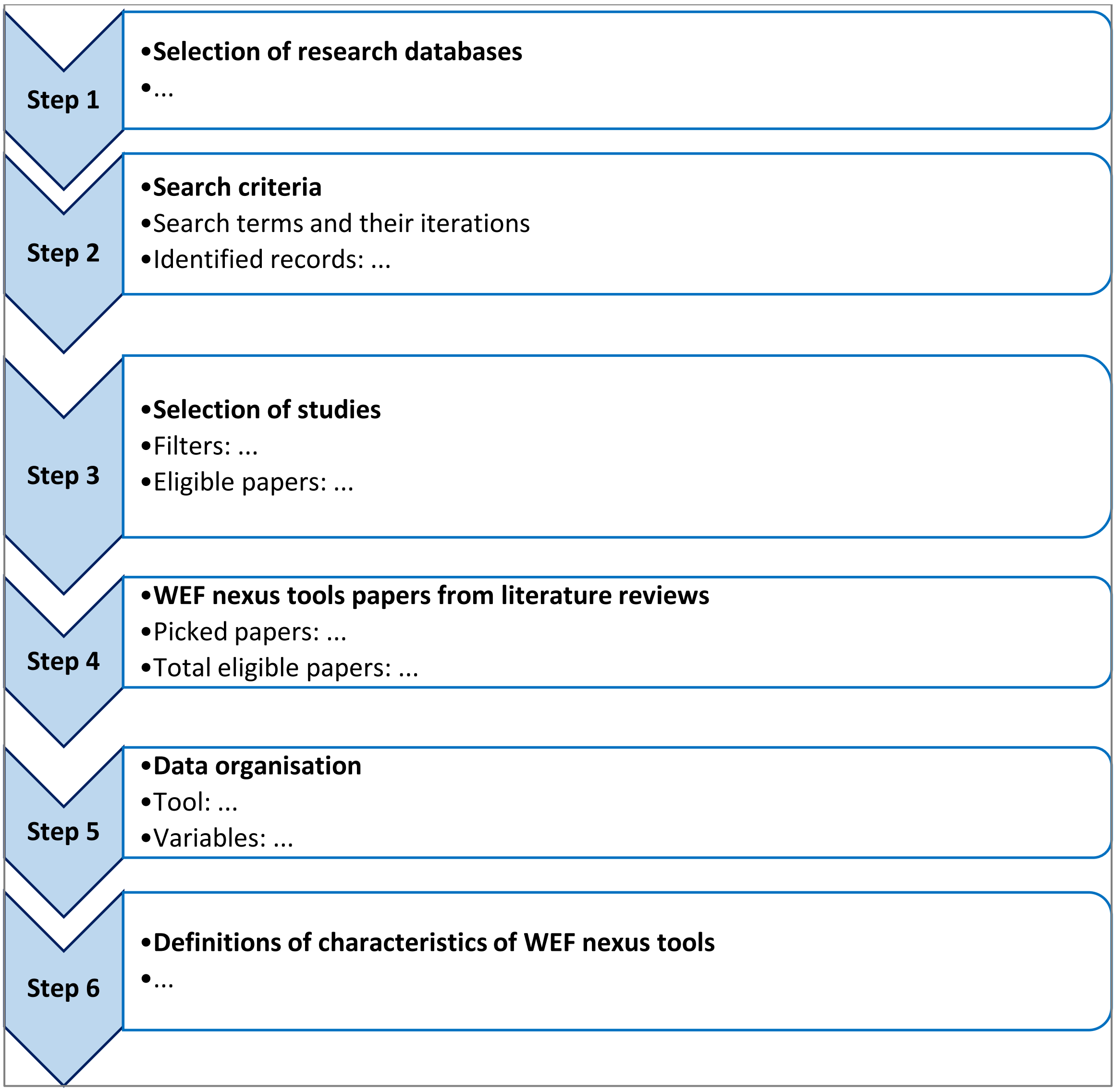

Figure 2: Systematic literature review methodology as PRISMA protocol flowchart adapted from (Moher et al., 2009)

2.4.1 Eligibility criteria

To limit the number of irrelevant articles, the study applied the population, indicator, comparison, outcome and study design (PICOS) strategy (Methley et al., 2014) (Table 1). The PICOS strategy informed the search strategy and the subsequent inclusion-exclusion criteria. Given that the WEF nexus is a fairly novel area of research, particularly its implementation and tools, broad eligibility criteria were adopted for publications mentioning the development and application of WEF nexus tools. However, only studies with uniquely named and operational WEF nexus tools were included to exclude anonymous, in-progress and non-operational tools.

Table 1: The adapted PICOS strategy used for literature searching

PICOS	Description
Population	WEF nexus
Indicator	WEF nexus tools, models, applications
Comparison	N/A
Outcome	Applicability characteristics of WEF nexus tools
Study designs	Qualitative, quantitative and mixed

2.4.2 Information sources and search strategy

The potentially relevant studies in the literature were searched using the same search criteria within two online literature databases, Scopus[2] and Web of Science Core Collection (WoS)[3]. These two multidisciplinary databases were selected for their comprehensive coverage and high-quality scientific publications that allow systematic review. Their journal coverage is also remarkably greater than other common databases, even in natural science and engineering disciplines. Citation searches were also conducted in reviews to identify WEF nexus tools and their corresponding publications that could be missed in Scopus and WoS databases, including those by international organizations such as Food and Agriculture Organization (FAO) and International Renewable Energy Agency (IRENA). The search criteria in the two databases (Scopus and WoS) involved searching topics using Boolean expressions. The search topics were formed from the keywords “nexus, tool, model, application, spatial, map, geographic information system, GIS” in various forms, together with iterations of “water, energy, food” and WEF. An open and unrestricted geographical scope was maintained since the WEF nexus is a relatively new and fast-evolving paradigm. An open timespan was also applied to capture all WEF nexus tools and versions. The details of the search topics used are presented in Table 2.

[2] https://www.scopus.com/ (02 July 2021)
[3] http://www.webofknowledge.com/ (02 July 2021)

Table 2: Search topics for retrieving documents related to WEF nexus tools in Scopus and WoS

Search topic (first row)	Search topic (second row)	Search topic (third row)
(water-energy-food) OR (water-food-energy) OR (energy-food-water) OR (energy-water-food) OR (food-energy-water) OR (food-water-energy) OR WEF OR WFE OR EFW OR EWF OR FEW OR FEW	AND nexus	AND (tool OR model* OR application OR "geographic information system" OR gis OR geospatial OR spatial OR map* OR web)

Peer-reviewed papers (articles, reviews), scientific book chapters, papers from proceedings and materials from special issue editorial material, institutional documents, including dissertations, theses, or technical papers, all written and published in English, were considered. Journal disciplines and impact factors were kept open because the WEF nexus approach, tools and integration of geospatial features are still novel. All records obtained from Scopus, WoS, and citation searches were combined to facilitate the removal of duplicates.

2.4.3 Screening and selection of studies

The focus remained on publications that delved into WEF nexus models, tools, applications, and spatial analysis methods and mapping such as GIS, emphasising capturing at least all three components of the WEF nexus: water, energy, and energy food. In line with the objectives of this systematic review, the titles, abstracts, and keywords of the searched studies were reviewed and screened for selection. The screening was in favour of publications on (i) WEF nexus tools that have an operational version(s) instead of proposed or work in progress, (ii) capturing at least all three components of the WEF nexus: water, energy, and food, and (iii) explicit mention of developing or using a WEF nexus tool (or model or application) with or without geospatial (GIS) mapping, analysis and visualization. The term 'land' was sometimes considered a proxy for the food component since it is a key element directly linked to food production. Secondly, books and chapters were excluded because they replicated some published journal articles. Eventually, the eligible papers were retrieved for review. These eligible papers and sources may not include all the WEF nexus literature. However, they best represent the previous work relevant to addressing and fulfilling our research questions and objectives.

2.4.4 Collecting data

A data extraction sheet was designed in simple, flexible, and functional MS Excel based on the study objectives. Key data on the selected papers were extracted from the eligible studies and organized in the data extraction sheet. These were organized in columns by the tool's characteristics, including acronym, authors/developers, year of initial development, availability, format/form, the spatial scale of application, geospatial capabilities, and the number of previous case studies. The sub-columns for availability contained general availability, web availability, and dead links. The sub-columns were web applications, desktop applications, code, Excel, serious games and unknown. The sub-columns under spatial scale of application presented five classes namely (i) global, (ii) continental / economic region / basin / transboundary, (iii) country / national, (iv) province / sub-basin / catchment, and (v) local including sub-catchment / municipal / city / town / household / project. The sub-columns under the number of case studies column included three classes according to frequency, namely low (one to three), moderate (four to 10), and high (more than 10).

2.4.5 Data items and analysis of studies

The characteristics of the WEF nexus tools used in this study were criteria briefly defined and described (Table 3) from previous related reviews (Flammini et al., 2014; IRENA, 2015; Shinde, 2017; Dargin et al., 2019) as well as authors' discretional synthesis.

Table 3: Definitions of characteristics of WEF nexus tools

Tool Characteristics	Description
WEF system tool (herein synonymous with model, application)	The mathematical relationships between food, energy, and water systems that simplify and represent reality by capturing their spatial and/or temporal dynamics and feedback between them. A WEF nexus tool is an intellectual construct that describes a system's structure and function to give insights into select attributes of a WEF system's physical, biological, economic, or social dimensions and dynamics (EPA, 2009; Saundry and Ruddell, 2020).
Availability	The quality or state of presence, ready reachability, and accessibility by public users[4].
Web availability	The quality or state of being available at a specific expected internet or online location[5].
Broken or dead links	A hyperlink on a web page that no longer works maybe because the destination web page no longer exists or has been moved, or an error[6].
Format	The form or type of the tool includes web applications, desktop applications, codes, Excel worksheets, and serious games/simulators[7].
Web application (or web app)	An application program usually hosted on a remote server and accessible through web browsers (Bourne, 2014; Sturm et al., 2017).
Desktop application (or desktop app)	An application that runs stand-alone and locally on a computer device such as a desktop or laptop[8].
Code	The symbolic arrangement of data or instructions in a computer program or the set of such instructions[9].
Excel worksheet	A collection of cells organized in rows and columns that keeps and manipulates data[10].
Serious game	A "learning by playing" decision-based platform, including role plays, that allows policymakers to play out scenarios and see what would bring the best outcome (Vamvakeridou-Lyroudia et al., 2017; Saundry and Ruddell, 2020).

[4] https://blog.amplexor.com/website-availability-what-is-it
[5] https://blog.amplexor.com/website-availability-what-is-it
[6] https://www.techopedia.com/definition/23236/broken-link; https://www.computerhope.com/jargon/b/broken_link.htm
[7] https://dictionary.cambridge.org/dictionary/english/format; https://www.collinsdictionary.com/dictionary/english/format
[8] https://encyclopedia2.thefreedictionary.com/desktop+application
[9] https://www.thefreedictionary.com/computer+code
[10] https://www.excel-easy.com/basics/worksheets.html

Table 3: Definitions of characteristics of WEF nexus tools, Continued

Tool Characteristics	**Description**
Unknown	When the form of the tool is not stated by the developers, previous users or literature[11].
Spatial scale	The spatial extent or level of application for the tool measured by area, distance or length, including ecological, hydrological and administrative[12] (Saundry and Ruddell, 2020).
Geospatial capabilities	Spatial mapping, visualization and analysis through the use of either open-source GIS or commercial products and software (Johnson, 2009; Janipella et al., 2019).
Case study (practice)	A published use of the tool in assessing real-life circumstances or simulating and modelling hypothetical scenarios; the application of Nexus research to real-world problems (Saundry and Ruddell, 2020; Vinca et al., 2021).
Low case studies	Refers to previous use of the tool in between one to three areas
Moderate case studies	Refers to previous use of the tool in between four to 10 areas
High case studies	Refers to previous use of the tool in more than 10 areas

[11] https://www.merriam-webster.com/dictionary/availability

[12] https://www.igi-global.com/dictionary/mapping-the-chromosome-through-a-novel-use-of-gis-and-spatial-analysis/43412

The tool characteristics presented in Table 3 constitute some desirable attributes in the intended users' applicability of WEF nexus tools. For example, the availability of and accessibility to a WEF nexus tool in the public domain are key prerequisites to its applicability by the intended users. Thus, tools' links provided by developers and previous users, such as web addresses and digital object identifiers (DOIs), were investigated for activeness. On encountering broken or dead links, a further basic search for the tool was conducted on the tool's related website or Google Search Engine[13] to explore alternative links. All evidence of the tools' characteristics was gathered from literature without contacting the authors/developers to avoid bias. This was necessary to ascertain what interested WEF nexus tools' users are likely to encounter on looking for WEF nexus tools on the internet. The results were presented as tables and charts for analysis, visualization, and interpretation.

2.5 Results and Discussion

The pursuit of the WEF nexus approach has seen the development of several computer-based tools for analysing, modelling, and simulating the WEF nexus in terms of resource supply, demand, nexus indicators and indices, for historic and present trends as well as future scenarios considering probable changes. The overarching intention of the tools is to assist planners, decision-makers, policy-makers and planners in integrated resources management. This section presents the results of reviewing 46 tools, without necessarily comparing them, and simultaneously acknowledging that the specific tools were developed for different purposes. It unpacks the general characteristics of the existing WEF nexus tools, as found in published literature from the latest to the earliest in terms of the time of development. This section presents the findings from reviewing the searched literature against the characteristics and criteria that were previously presented in Table 3.

2.5.1 Literature Search

The detailed results of the search and selection process are presented in the PRISMA flowchart diagram in Figure 3. Initially, 1057, 1185 and 83 records were obtained from Scopus, WoS, and citation searches, from which duplicates were removed in EndNote to remain with 1543 papers. After screening and selecting the 1543 studies with the inclusion and exclusion criteria, 183 papers were eventually yielded and retrieved for review, whose findings are presented in the succeeding sections.

[13] https://www.google.com

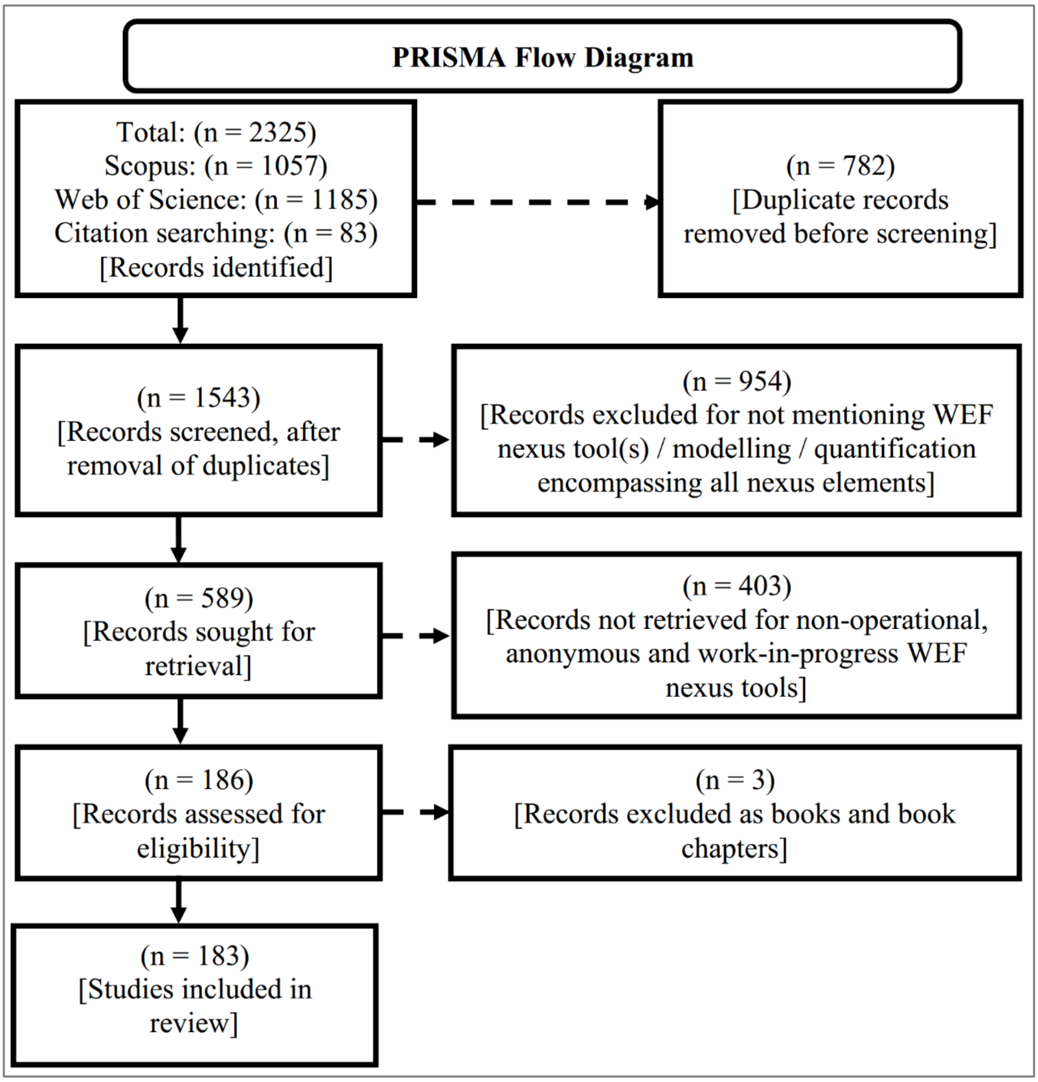

Figure 3: The PRISMA 2020 framework and flow diagram with search results, as adapted from (Haddaway et al., 2021a,b; Page et al., 2021a,b).

2.5.2 Trends in Development of WEF Nexus Tools

The retrieved literature systematically yielded 46 WEF nexus tools (Table 4 and Appendix 1). Logically and at first sight, this is quite a large number in contrast to previous reports of a lack of WEF nexus tools (Byers, 2015; Liu et al., 2017; Nhamo et al., 2020a; Naidoo et al., 2021).

Table 4: Brief Summaries of Existing WEF Nexus Tools.

WEF Nexus Tool	**Short Description**
WEF Nexus Discovery Map (1)	WEF Nexus Discovery Map is a map-based pool/database of catalogued and classified WEF nexus information from otherwise geographically and topically diverse independent and academic communities worldwide. It shows WEF nexus projects' specific information, such as the institution that produced the work, local collaborators, relevant web page, and point of contact. The WEF Nexus Discovery Map dashboard incorporates the WEF Nexus Index Map (Arenas et al., 2021).
BP-DEMATEL-GTCW (2)	Back Propagation neural networks-DEcision Making Trial and Evaluation Laboratory-Game Theory Combination Weight (BP-DEMATEL-GTCW) Model is a two-step measurement model for the symbiotic and symbiotic level indices used to study the nexus in the form of the WEF ecosystem from the perspective of WEF symbiosis. Its applications include identifying key influencing factors that affect the symbiotic security of the WEF ecosystem (Chen and Chen, 2021).
ITEEM (3)	Integrated Technology-Environment-Economics Model (ITEEM) integrates various models for technology (grain processing, drinking water treatment, environment (watershed model for hydrology, water quality, crop production, nutrient cycling), and an economics model for assessing total benefit that includes non-market evaluation of environmental benefits (Li et al., 2021).
WEF-Sask (4)	Water-Energy-Food (WEF) - Sask (WEF-Sask) Model integrates the production (supply) and demand sides of WEF systems into a single system-of-systems model using the system dynamics approach to gain insights into inevitable trade-offs and synergistic interactions between WEF systems under challenges brought by socioeconomic and climatic changes and limited water resources (Wu et al., 2021).
CALFEWS (5)	California Food-Energy-Water System (CALFEWS) links the operation of state-wide, inter-basin transfer projects with coordinated water management strategies abstracted to the scale of irrigation/water districts to describe the integrated, multi-sector dynamics that emerge from the coordinated management of surface and groundwater supplies (Zeff et al., 2021).
NeFEW (6)	Nexus of Food, Energy, and Water (NeFEW) Toolbox is a data analysis toolbox for synthesizing available global data to enable estimating country-specific estimates of water resources (blue, green, grey) required to produce different types of food and energy, the energy required per quantity of water or agricultural product supplied, and CO_2-equivalent emissions associated with water and energy provision (Sadeghi et al., 2020).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
MAXUS Model (7)	MAXUS highlights, simulates, and optimizes inter-sectoral and international development strategies in the WEF sectors. The model consists of an objective function, balances, dimensions, constraints and decision variables (Burger and Abraham, 2020).
WEF Nexus SD (8)	The Water-Energy-Food Nexus System Dynamics (WEF Nexus SD) Model is based on system dynamics to study intricate connections between WEF and specific supply-and-demand mechanisms of water resources in each sub-system. The sub-systems include the external social, economic, and eco-environmental, all integrated by the model to determine the dynamic balance of water resources (Chen and Chen, 2020).
FPC (9)	Farm Performance Calculator (FPC) contains data and conversion coefficients derived from the (FArming Tools for external nutrient Inputs and water MAnagement) FATIMA project to calculate indicators and conduct energy, economic and environmental analysis for a simplified evaluation and analysis of the WEF nexus at the farm level. The main input for the calculator consists of agricultural and energy, while the main output consists of computations for the energy, water and food indicators (Fabiani et al., 2020).
WEF-P (10)	Water-Energy-Food Nexus - Phosphate (WEF-P) Tool is an adaptation of the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015). WEF-P assesses the impact of various scenarios and possible responses to resource management needs, by considering the supply the supply chain of the final product in terms of its resource consumption, including the set of processes that pass materials forward and various organizations/individuals directly involved in the flow of the products (Lee et al., 2020).
SD-WFE (11)	System Dynamics Water-Food-Energy (SD-WFE) Model is a spatiotemporal disaggregated WEF nexus model that assesses water and food supply security considering ecosystem provisioning services. The model contains modules for population, water, agriculture, and energy (Ravar et al., 2020).
WEST (12)	WEST (Water Economy Simulation Tool) is a simulation model that incorporates water, energy, food, and detailed economic data, usable for standalone analysis or incorporated, to show how jobs and economic growth interact with surface and groundwater use, food and energy (Reimer et al., 2020).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
MIFCP-WEFN (13)	Multi-level Interval Fuzzy Credibility-constrained programming Water-Energy-Food Nexus (MIFCP-WEFN) Model helps plan the regional-scale WEF nexus system by identifying the optimal agricultural water resources management schemes through the leadership of water resources managers and the feedback of two diverse followers (i.e. managers for energy and agriculture) (Yu et al., 2020).
NEST (14)	NExus Solutions Tool (NEST) is an open modelling platform for integrated energy-water-land (EWL) systems analysis under global change by a hard-linked integration of multi-scale energy-water-land resource optimization framework with distributed hydrological modelling. It integrates a distributed hydrological model and a resource supply planning model (Vinca et al., 2020).
The Integrative Analytical model for the WEF nexus (15)	Integrative analytical model for the Water-Energy-Food nexus (iWEF) is an Analytic Hierarchy Process (AHP)-based model that establishes quantitative relationships among WEF nexus sectors, as well as an integrated nexus index that indicates resource utilization and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention (Nhamo et al., 2020a).
WEF Nexus Index (16)	The Water-Energy-Food (WEF) Nexus Index is a web-based WEF nexus global visualization map comprising an index that is a composite indicator derived from integrating WEF resource sectors' indicators. Within each resource are equally weighted 'access' and 'availability' sub-pillars, as well as relevant indicators from a total of 21 (Simpson et al., 2022).
AWEFSM (17)	Agricultural Water-Energy-Food Sustainable Management (AWEFSM) Model integrates multi-objective programming, nonlinear programming, and intuitionistic fuzzy numbers into a general framework for the sustainable management of the limited water-energy-food resource in an agricultural system (Li et al., 2019).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
GREAT for FEW (18)	GIS-based Regional Environmental Assessment Tool for Food-Energy-Water nexus (GREAT for FEW) is based on the life cycle assessment (LCA) method for evaluating the FEW inter-linkages and informing decision-makers of the co-benefits and trade-offs from a wide variety of investments and policies for the present and the future. It combines a nexus assessment framework and a web-based GIS-enabled nexus platform that consists of a conceptual model, a database, and calculation methods (Lin et al., 2019).
EPAT (19)	Energy Portfolio Assessment Tool (EPAT) is a scenario-based holistic nexus tool and platform for energy stakeholders and policymakers to create and evaluate the sustainability of various WEF nexus scenarios (Mroue et al., 2019).
WHAT-IF (20)	Water, Hydropower, Agriculture Tool for Investment and Financing (WHAT-IF) is an open-source hydro-economic optimization model incorporating representations of the water, agriculture, and power systems in a holistic framework to explore joint development of nexus-related infrastructure and policies and evaluate their economic impact, as well as the risks linked to uncertainties in future climate and socio-economic development (Payet-Burin et al., 2019).
K-WEFS (21)	Karawang Water-Energy-Food (WEF) Security (K-WEFS) Model is a system dynamic model that assesses the WEF nexus based on four scenarios: changes in population growth, agricultural land conversion rate, per-capita resource consumption, and the development of artificial ponds and solar energy (Purwanto et al., 2019).
WEFSiM (22)	Water-Energy-Food (WEF) nexus Simulation Model (WEFSiM) is a system dynamics algorithm-based computer simulation and optimization model that calculates the supply and consumption, availability, and reliability of water, energy, and food resources nationwide considering the interconnections of resources (Wicaksono and Kang, 2019).
Daily (23)	Daily Model applies cost-benefit analysis to assess WEF nexus scenarios from integrating RiverWare, HEC-HMS, and CropWat that simulate hydrological processes, irrigation water requirements, and water allocation to hydro-energy generation and irrigation water supply (Basheer et al., 2018).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
DAFNE (24)	The Decision-Analytic Framework to explore the water-energy-food NExus in complex and transboundary water resources systems of fast-growing developing countries (DAFNE) approach facilitates the quantitative assessment of the social, economic, and environmental impacts of expanding energy and food production in complex physical and political contexts, in interconnected natural and social processes, where the institutional setting involves multiple stakeholders and decision-makers. The approach consists of a Decision-Analytic Framework (DAF) for Participatory and Integrated Planning (PIP), an integrated WEF modelling framework and a web-based Negotiation Simulation Lab (NSL) (ETHZÜRICH, 2018).
SIM4NEXUS Models and Serious Game (25)	Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe (SIM4NEXUS) Models and Serious Game consist of a WEF system dynamic integrated model and serious games for investigating potential plausible cross-nexus implications and synergies under different climate change and socioeconomic pathway scenarios due to policy interventions for 12 multi-scale case studies ranging from regional to global (Sušnik et al., 2018).
UCEC (26)	Urban Circular Economy Calculator (UCEC) is an online open-access tool for cities to develop different circular economy scenarios associated with WEF management. Based on energy accounting urban dynamic modelling, it uses WEF inputs from urban managers and policymakers to display the analysis of different urban circular economy scenarios considering technological roadmap alternatives performances from policy and technology solutions (Xue et al., 2018).
ABM-SWAT Model (27)	Agent-Based Model - Soil and Water Assessment Tool (ABM-SWAT) is an integration of ABM and SWAT that assesses the impact of climate and human/anthropogenic changes on the water, energy, food, and ecosystem sectors and characterizes the resulting trade-offs through a set of generic metrics related to the sustainability of water availability (Khan et al., 2017).
Nexus Game (28)	Water-Food-Energy Nexus Game is an integrated ‘hardware’ simulation game addressing the interrelated challenges of WEF production to meet demand. It is set on two riparian countries sharing a transboundary river basin, representing inter-ministerial and international negotiations wherein players encounter and learn potential technological solutions and relational challenges to reduce their WEF footprints (CSS et al., 2017).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
WEF Model (29)	Water-Energy-Food (WEF) Model is a system dynamics-based model that captures the interactions between WEF at the household scale and end-use level by estimating WEF demand and the generated organic waste and wastewater quantities and investigating the impact of change in user behaviour, diet, income, family size and climate (Hussien et al., 2017).
Q-Nexus (30)	The Q-Nexus model is a quantitative WEF nexus assessment, simulation and optimization framework and platform to quantify, plan, simulate and optimize water, energy, and food as an interlinked system of resources that directly and indirectly affect one another. The model enables the analysis of WEF planning scenarios and policy options based on dynamic demand, technology and resource allocation (Karnib, 2017).
NexSym (31)	Nexus Simulation System (NexSym) is a modular tool based on a simulation and analytics framework for explicit systems dynamic modelling of local techno-ecological interactions relevant to WEF operations. It integrates models for ecosystems, technology, WEF production and consumption components, including waste treatment (Martinez-Hernandez et al., 2017).
WEFO Model (32)	Water, Energy and Food security nexus Optimization (WEFO) is an integrated multi-period socioeconomic model analysis framework and tool for predicting how to satisfy WEF demands based on model inputs representing production costs, socioeconomic demands, and environmental controls. WEFO's management objective is to minimize the total system cost, a sum of energy supply, water supply, electricity generation, food production, and CO_2 emission mitigation costs (Zhang and Vesselinov, 2017).
SEWEM (33)	System-wide Economic-Water-Energy Model (SEWEM) is an advanced hydro-economic optimization model analysing basin-wide energy production alternatives and energy demand restrictions for agricultural and industrial production and water supply systems (Bekchanov and Lamers, 2016).
BRAHEMO (34)	BRAhmaputra HydroEconomic MOdel (BRAHEMO) integrates physically-based spatially distributed hydrologic modelling, hydro-economic modelling, and ex-post scenario analysis to elicit the conditions of conflict and alignment of development trajectories (Yang et al., 2016b).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
IBMR-MY (35)	Indus Basin Model Revised-Multi Year (IBMR-MY) is a hydro-agro-economic model extended with an agricultural energy use module. Its objective function maximizes the net economic benefit (from crop production and hydropower generation) of water uses in the basin (Yang et al., 2016a).
Pardee RAND WEF Security Index (36)	Pardee RAND Water-Energy-Food (WEF) Security Index is an online interactive WEF nexus security index with an unweighted geometric mean of three sub-indices, each for the three WEF sectors. Each sub-index comprises two or more indicators reflecting resource availability and accessibility (Willis et al., 2016).
WEF Nexus Tool 2.0 (37)	The Water-Energy-Food (WEF) Nexus Tool 2.0 is a scenario-based tool that consists of inputs that reflect national food, water, and energy strategic options and allows for creating and assessing different scenarios to achieve sustainable resource management strategies for national food production. The tool uses an input-output modelling framework and food as an entry point to calculate nexus resource flows and interactions and greenhouse gas (GHG) emissions for a food self-sufficiency level (Daher and Mohtar, 2015).
PRIMA (38)	Platform for Regional Integrated modelling and Analysis (PRIMA) is an innovative modelling system to simulate interactions among natural and human systems at scales relevant to regional decision-making. PRIMA aims to enhance scientific understanding and facilitate effective decision-making related to regional interactions among climate, energy, hydrology, land use, and socioeconomics. PRIMA’s modelling framework integrates various models of regional climate, hydrology, agriculture and land use, socioeconomics, and energy systems using a flexible coupling approach. Due to its modular framework and structure, PRIMA is customizable, portable and flexible (Kraucunas et al., 2015).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
EWF Nexus Tool (39)	Energy-Water-Food (EWF) Nexus Tool integrates energy, water, and food life cycle assessment in one robust, holistic systems model of sub-systems at an appropriate resolution. The EWF Nexus Tool uses life cycle assessment principles to translate system outputs into environmental assessment scores, by operating through the four stages of life cycle assessment: the goal and scope definition, the life cycle inventory analysis; the impact assessment; and the interpretation of the results (Al-Ansari et al., 2014).
WEF Nexus Assessment 1.0 (40)	Water-Energy-Food (WEF) Nexus Rapid Appraisal (or Nexus Assessment 1.0) Tool rapidly informs nexus-related responses regarding strategies, policy measures, planning and institutional set-up, or interventions regarding bio-economic pressures. It provides users with ten nexus context analysis indicators and 30 nexus intervention analysis indicators. The set of intervention scenarios includes power irrigation, bioenergy, hydropower and water desalination interventions from the perspective of water, energy, food, labour, and cost components (Flammini et al., 2014).
Nexus Webs (41)	Nexus Webs is a conceptual-analytical model of the components and linkages in a river basin representing how water use changes impact livelihoods and wellbeing. The four linked components include water use, assets, ecosystem services and wellbeing (Overton et al., 2013).
CLEWs (42)	Climate-, Land-, Energy- and Water-systems (CLEWs) tool applies a module-based approach to quantitatively and simultaneously assess/explore land, energy and water resource systems as closely linked resources (and climate) within a modelling framework that integrates detailed models from different tools. The tool iteratively passes data between sectoral models (Howells et al., 2013).
WEAP – LEAP (43)	Water Evaluation and Planning System – Long-range Energy Alternatives Planning System (WEAP-LEAP) were integrated to become WEAP-LEAP for integrated research planning, analyses and decision-making of the closely interlinked energy and water systems. They are connected seamlessly by a common 'wizard' that allows exchanging parameters and outputs, such as hydropower generated or cooling water requirements, water supply characteristics for projecting energy demand, hydropower modelling and consistent weekly time-step calculations (SEI, 2012).

Table 4: Brief Summaries of Existing WEF Nexus Tools, Continued

WEF Nexus Tool	**Short Description**
Foreseer (44)	The Foreseer Tool is a modular model for tracing and visualizing, using Sankey diagrams, the influence of future demand scenarios on requirements for energy, water, and land resources. The tool is based on a set of linked physical models for energy, water and land, or any other customized analyses such as climate change, technological change, or other effects (Allwood et al., 2016).
ANEMI (45)	ANEMI is an integrated assessment model of global change that emphasizes the role of water resources. The model uses feedback processes among its sub-systems and system dynamics simulation principles to analyse changes in the Earth system. ANEMI3 assesses and describes the state of and interactions between the Earth system's model sub-systems (or sectors), mainly climate system, carbon, nutrient and hydrologic cycles, population dynamics, land use, food production, sea-level rise, energy production, energy, economy, persistent pollution, water demand and water supply development (Davies and Simonovic, 2010).
MuSIASEM (46)	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an integrated diagnostic and simulation tool that characterizes the metabolic pattern/flows of energy, food and water and their interlinkages about socio-economic (e.g. population dynamics) and ecological variables (e.g. land-use changes, greenhouse gas emissions) simultaneously. The MAGIC Nexus Game is a serious game based on MuSIASEM, to expose players to the main trade-offs and co-benefits in the nexus using a quantitative framework of relations between the nexus elements based on environmental footprint indicators (Giampietro et al., 2009).

From Figure 4, the existence of WEF nexus tools pre-2011 (MuSIASEM (46), ANEMI (45)) shows that the WEF nexus concept existed before 2009. The year 2011 was just a turning point when the concept gained attention and momentum in wider research and policy agenda circles. It is evident from Figure 4 that the development of WEF nexus tools started around 2009-2012, and has been gaining momentum thereafter, as evidenced by the increasing annual trends and cumulative total number with time. It can be observed that the annual rate of development of WEF nexus tools was slow during 2009-2010; increased in 2012 but stagnated until 2015; increased in 2016-2017, and then fell in 2018, followed by consecutive increases in 2019-2020 which is the peak of the period under review. The largest number (11) of developed WEF nexus tools was recorded in the year 2020, including NEST (14), integrative analytical model for the WEF nexus (15) and WEF Nexus Index (16); while an almost half year of 2021 (January to 02 July) recorded five (5) developed WEF nexus tools.

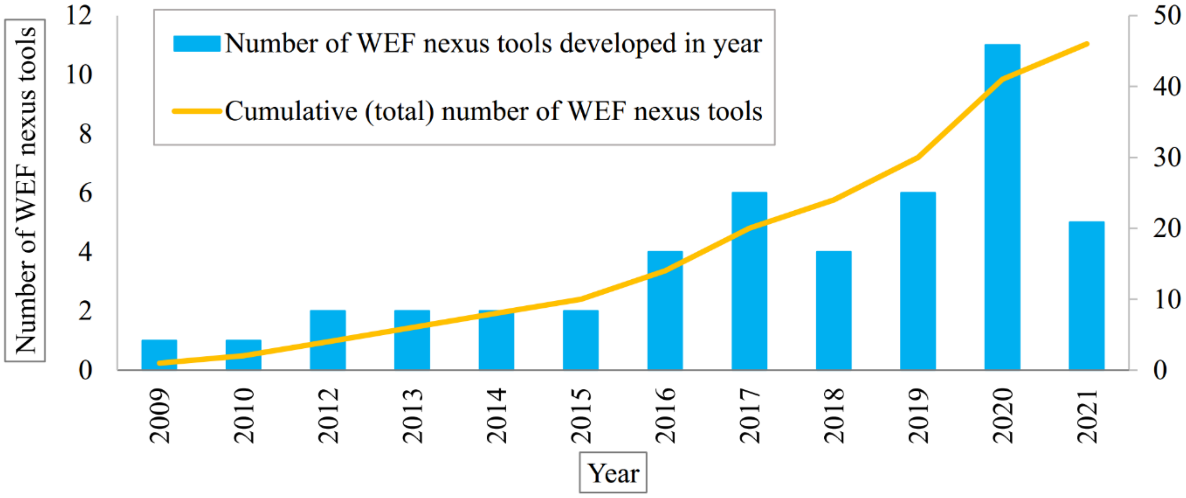

Figure 4: Trend in the development of WEF nexus tools

These increasing trends in developed WEF nexus tools with time were also observed by Shinde (2017) and bear witness to the continuously increasing momentum of the WEF nexus agenda in research and maybe practice. This implies that implementing the WEF nexus, which has been lagging, is catching up with WEF nexus agenda research and dialogues. The progressive trend in WEF tools development, especially post-2011, could have been motivated by the increased traction of the WEF nexus concept in international policy and research, including the iconic World Economic Forum Water Initiative (WEF, 2011) and Bonn2011 Conference on The WEF Security Nexus Solutions for the Green Economy (Hoff, 2011). The rising trends in WEF nexus tools development, especially a few years later in 2015, also coincide with the period in which related Sustainable Development Goals (SDGs) were adopted and enforced, including SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy).

Judging from the past and current trends, more WEF nexus tools are being developed. They will likely continue to be developed in the future to provide researchers, practitioners, non-practitioners, decision- and policymakers with a wide range of tools that can be used in implementing the WEF nexus approach. With such a relatively large quantity of developed WEF nexus tools at our disposal, it remains to be theoretically and practically investigated the key qualitative characteristics of these reported tools, including their availability to interested users, their format, spatial and temporal scales of application, geospatial analytic capabilities, and previous in cases studies. Such critical questions and issues need to be addressed to guide and inform users on selecting the WEF nexus tools that suit their case study contexts. The succeeding sections present the results of the theoretical assessment of published literature on these key characteristics of WEF nexus tools.

2.5.3 Existing WEF Nexus Tools

The 46 WEF nexus tools found in the literature are summarized in Table 4, including their names, developers, year of publication and brief description.

The characteristics of the 46 WEF nexus tools are presented in Appendix 1, including availability, format, spatial scale, geospatial capabilities, and the number of previous case studies.

2.5.4 Availability and Format of WEF Nexus Tools

Availability and accessibility are prerequisites that allow wide use of WEF nexus tools by users for improved nexus-friendly decision-making (IRENA, 2015). Logically, interested users can only choose from and use tools readily available to them.

Despite the relative abundance of WEF nexus tools that have been developed (Table 4 and Appendix 1), only a minority (39%) of the existing 46 tools are available to public users. The rest (61%) cannot be found in the public domain (Figure 5). This unavailability of WEF nexus tools echoes with Vinca et al. (2020), who observed that existing WEF nexus tools and data are not always openly availed. Antle and Valdivia (2021) reiterated that modelling tools should be publicly available and well-documented for capacity building, knowledge transfer and transparency.

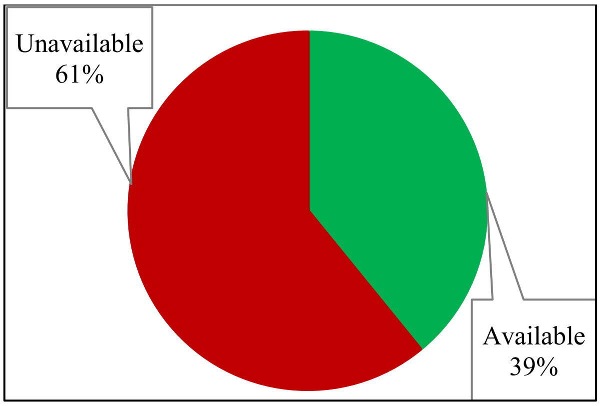

Figure 5: General claimed availability of WEF nexus tools

Of all the 46 tools, only 43% claimed to be hosted on the public web domain (Figure 6a and Appendix 1). Still, reality confirms that one in five of this category is dead links (Figure 6b and Appendix 1) which cannot be located where developers and previous users claim them to be or by searching online.

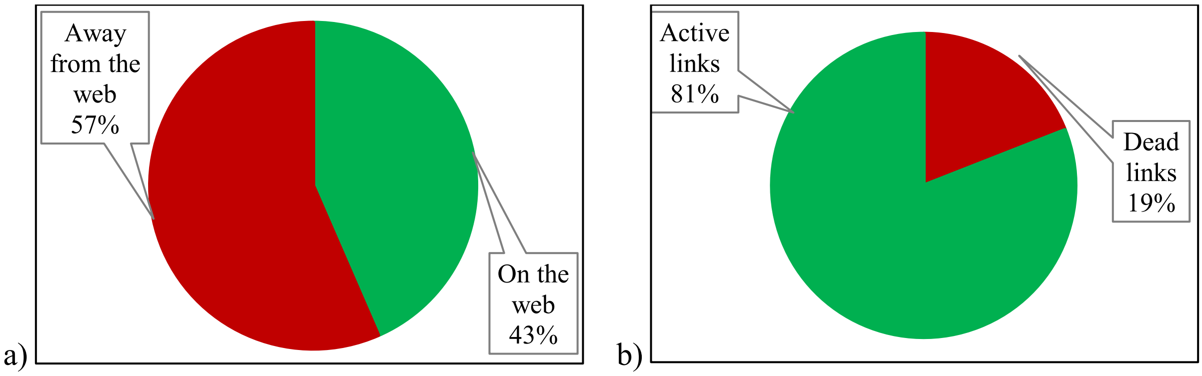

Figure 6: (a) Claimed availability of WEF nexus tools in the public domain, (b) Real web availability of WEF nexus tools

These readily unavailable and inaccessible WEF nexus tools include DAFNE (24), PRIMA (38), WEF Nexus Assessment 1.0 (40), Foreseer (44) and MuSIASEM (46). For instance, DAFNE (24) and its interactive Negotiation Simulation Laboratory (NSL) portal is restricted only to practitioners and non-practitioners who were part of the initial project from the Zambezi and Omo-Turkana river basins.

The format for the majority (≈ 48%) of all existing tools is not stated and is unknown (Figure 7 and Appendix 1). These include some of the promising tools whose conceptual frameworks are clearly laid out, such as AWEFSM (17), WEFSiM (22), WEFO (32), EWF Nexus Tool (39) and

Nexus Webs (41). They are not readily available and accessible to interested users for application in case studies.

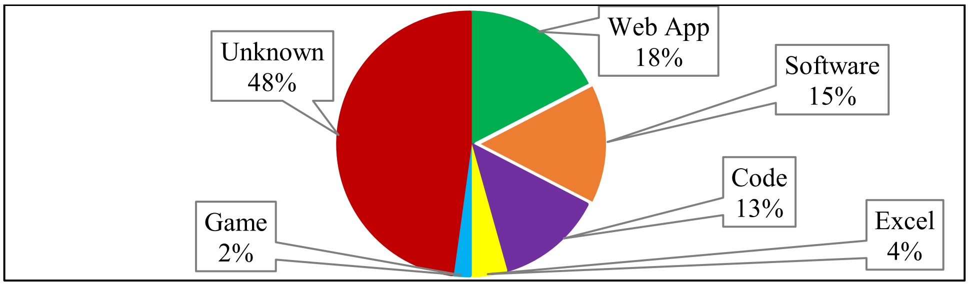

Figure 7: Format of WEF nexus tools

Web applications dominate for those tools whose format was stated or observed, followed by desktop applications, codes, spreadsheets, and serious games, in that order of prevalence. Concerning format, the majority are web applications (≈ 18%). These include DAFNE's (24) Negotiation Simulation Laboratory (NSL), whose access is limited to DAFNE project partners and stakeholders (Melenhorst et al., 2018). This hinders its use in other areas beyond the river basins wherein it was developed and tested. Other web-based tools include Q-Nexus (30), WEF Nexus Tool 2.0 (37) and Pardee RAND WEF Security Index (36). Some web-based tools, including WEF Nexus Index (16), WEF Discovery Map (1) and Pardee RAND WEF Security Index (36), are mere visual portals and platforms that lack essential WEF nexus quantitative analytic capabilities but provide essential information on the WEF nexus. With such tools, interested users can neither input nor analyse their own case study data in these tools; they can only retrieve prepared information on the preloaded case studies.

The second-largest proportion (≈ 15%) of WEF nexus tools is claimed by desktop applications such as CALFEWS (5), NeFEW (6), WEF (29) and NexSym (31). However, running the NeFEW (6) tool requires MATLAB, thus requiring MATLAB programming competence for interested users. Compiled desktop applications types of tools lack flexibility in cases where a user may desire to link or integrate them with other models, or adapt the code for specific study purposes such as interdisciplinary policy analysis (Foster et al., 2017).

Codes type of tools claim approximately 13% of the tools and are archived in GitHub[14] and Zenodo[15] online libraries. These include NEST (14), WHAT-IF (20) and ANEMI (45). GitHub is a code hosting platform for project collaboration and version control, while Zenodo is an open dissemination research data repository. The availability of these codes is good for transparency and flexibility for integration and customization, especially for users knowledgeable about programming. However, this category of tools may be complex for use

[14] https://www.w3schools.com/whatis/whatis_github.asp
[15] https://help.zenodo.org/

by non-professional users due to programming competence requirements and lack of Graphical User Interface (GUI).

Excel worksheets type of tools claim approximately 4% of WEF nexus tools and away from the public web domain. These include FPC (9) and integrative analytical model for the WEF nexus (15), whose access must be sought from the authors and developers by interested parties. This poses a potential barrier to their wide use by interested users, because their accessibility depends on the willingness and time taken to share the tool by the developers.

Approximately 2% of WEF nexus tools are serious games, including Nexus Game (28), Serious Game for SIM4NEXUS (25), and MAGIC Nexus Game (46). Together with DAFNE's (24) NSL, these are 'edutainment' tools that provide a safe virtual online environment for negotiating and 'learning by planning' on implications of participants' choices, decisions, and actions in the WEF nexus. By playing these serious games, players are virtually exposed to the WEF nexus dynamics, thus building capacity and providing testbeds for policies, strategies, interventions and scenario planning.

Despite their web availability and analytical capabilities, some tools only apply to their case study areas of original development and testing. For example, the current version of GREAT for FEW (18) can only be applied only in Taiwan wherein it was originally developed and tested, because it lacks flexibility and key information for other areas from the user's perspective (Lin et al., 2019). The same applies to WEF Nexus Tool 2.0 (37), whose geographical scope was originally developed for Qatar (Daher and Mohtar, 2015), and SIM4NEXUS (25) models and games, which were specifically developed for the context of European countries (Sušnik et al., 2018). By default and design, this can limit the tools' applicability in other areas with different conditions despite their potential.

2.5.5 Spatial Scales of Application and Case Studies of WEF Nexus Tools

Most tools (approximately 48%) apply to large spatial scales such as continental, regional, transboundary basin, and national, followed by medium and local scales (Figure 8 and Appendix 1).

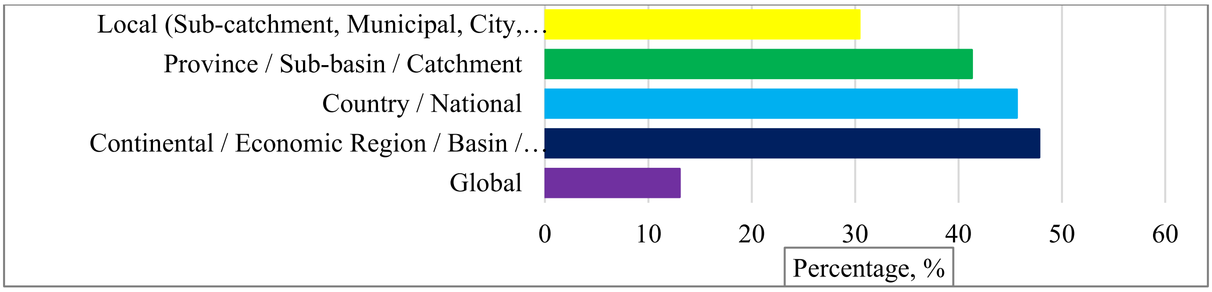

Figure 8: Spatial scales of application of documented WEF nexus tools

The large-scale tools include ANEMI (45), WEF Nexus Index (16) and Pardee RAND WEF Security Index (36), and they apply to aggregate-level studies that inform WEF policy- and decision-making. Thus, these large-scale tools are inappropriate for local-scale studies. This highlights a gap for local-scale tools that can model, simulate and analyse local WEF nexus for assessing challenges, impacts, interventions and adaptation to change that can promote sustainable development at the grassroots level (Terrapon-Pfaff et al., 2018). However, some tools tend to be scale-selective. For example, ANEMI 3, WEF Nexus Tool 2.0 and the Water-Energy-Food (WEF) model are most appropriate for global, national and household scales, respectively (Davies and Simonovic, 2010; Daher and Mohtar, 2015; Hussien et al., 2017). This tendency of tools to be specific in application scales may limit their applicability in case studies of different scales. WEF nexus tools should be multi-scalar, flexible and adaptable across geographic scale and scope, only requiring new, specific location-adapted inputs and data (IRENA, 2015). For example, the integrative analytical model for the WEF nexus is applicable at the regional scale (southern Africa) (Mabhaudhi et al., 2019), national scale (South Africa) (Nhamo et al., 2020a) and local scale (Sakhisizwe Local Municipality) (Nhamo et al., 2020b), respectively. However, developing multi-scalar tools is elusive due to different input data requirements at different scales bound by ecological, hydrological and administrative boundaries. To be widely used in implementing the WEF nexus approach, WEF nexus tools should be accessible, especially to developing country analysts, and applicable to finer geographical coverage (Bazilian et al., 2011).

2.5.6 Geospatial Analytic Capabilities in WEF Nexus Tools

Out of the 46 tools that were reviewed, only less than one-third (≈30%) possess geospatial capabilities (Figure 9 and Appendix 1).

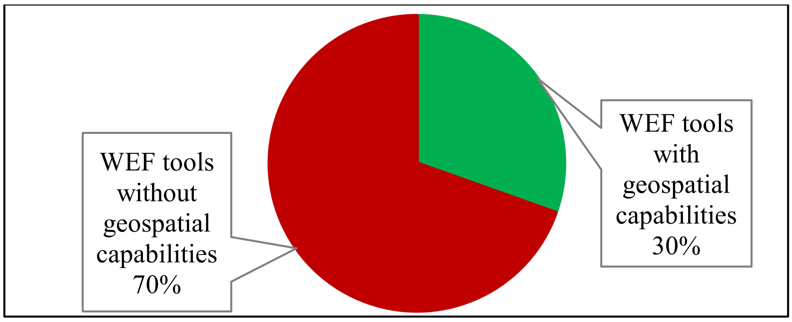

Figure 9: WEF nexus tools and their geospatial capabilities

The rest (≈70%) can only aggregate and generalize the WEF nexus in their analyses or display, without performing geospatial mapping and visualizing the WEF nexus. Thus, this majority cannot characterize the spatial dynamics of the WEF nexus, which poses a big limitation to the tools because WEF resources are spatially distributed in nature. This concurs with (Shannak et al., 2018; Ravar et al., 2020), who reported that even though WEF resources are exposed to intense variations in time and space, most presented models are not spatially or temporally disaggregated, which gives rise to deviation from the reality.

2.5.6.1 Use of GIS in WEF nexus studies

GIS has found application in analysing the spatial dynamics of the WEF nexus, with or without explicit mention of specific WEF nexus tools. For example, GIS tools and inputs were loosely coupled to a WEF nexus analysis method to evaluate the sustainability of WEF interventions (Yuan and Peng, 2017) and analyse WEF nexus hotspots by spatially mapping WEF resources demand and supply (Daher et al., 2019). Shannak and Vittorio (2020) developed a web-based GIS application that allows the selection of locations for growing a certain quantity of a specific crop and calculating water, land, and energy requirements over different spatial locations. The innovative tool uses satellite imagery to identify major environmental features that are important for analysis, therefore applicable in areas with scarce data for natural resources. In another study, Daccache et al. (2014) used a gridded water balance model's integrated framework with a geodatabase and GIS to assess irrigated agriculture's water and energy footprint in the Mediterranean region. They highlighted the synergies and trade-offs between strategies for saving water, reducing greenhouse gas emissions and/or intensifying food production. Ramirez et al. (2021) applied GIS-based tools, data and a levelized cost of water (LCOW) methodology to assess the impacts of wastewater reuse in agricultural irrigation on the WEF nexus in the North-Western Sahara Aquifer System (NWSAS). They captured the system's spatial dimension, matched wastewater supply and water demand points, identified demand hotspots, and evaluated techno-economically viable wastewater treatment options. In the same region and aquifer system, Almulla et al. (2020) used the CLEWs' and Transboundary River Basins Nexus Approach – United Nations Economic Commission for Europe (TRBNA-UNECE) frameworks to develop an open-access GIS-based model for WEF nexus specifically for North-Western Sahara Aquifer System (NWSAS). The model uses non-GIS and GIS inputs as well as a levelized cost of electricity (LCOE) approach in (i) identifying the location and extent of irrigated cropland, (ii) estimating water demand, (iii) estimating electricity requirements for groundwater irrigation, (iv) evaluating the selected supply options to meet the electricity demand, (v) suggesting the least-cost energy configuration in each location.

Gondhalekar and Ramsauer (2017) used a GIS-based WEF nexus urban planning approach that includes intensive urban agriculture in the City of Munich (Germany). They discovered that benefits to be accrued include providing 66% of local demand for fruit and 246% of local demand for vegetables. In addition, coupling wastewater recycling with rainwater harvesting could save a quarter of the current freshwater supply. Similarly, biogas generation from human sewage could save a fifth of the current electricity supply. Haji et al. (2020) developed and applied a GIS-and-AHP-based geospatial risk analysis approach for the WEF nexus in various agricultural systems in Qatar. They observed that weather factors (e.g. temperature, solar radiation, humidity) are the risky critical factors in open field farms. In contrast, groundwater factors are critical in conventional and hydroponic greenhouses. Interestingly, hydroponic greenhouses were more water-efficient than open fields, consuming more energy for cooling and desalination requirements.

These case studies showcase the vast potential and value of GIS integration with WEF nexus tools for the spatial characterization of the WEF nexus dynamics.

2.5.6.2 Coupling WEF nexus tools with GIS

WEF resources vary in space and time, thus requiring spatial and temporal disaggregation with appropriate tools for comprehensive analysis that can inform improved planning for sustainable management. As much as it is necessary to determine aggregate and average values in WEF nexus analysis, it is equally important to characterize its dynamics in space and time because different areas have different WEF nexus conditions such as resources endowments, utilization and demands. This spatial-temporal characterization can be achieved by running several point measurements and analysing the WEF nexus, which is time-consuming and tedious. Fortunately, this can be done simultaneously, efficiently and effectively using geospatial features in WEF nexus tools, either as built-in or loosely-coupled for pre-processors of input datasets and/or post-processors of outputs. Though less common, the former method hard-links geospatial features and the WEF nexus tool such that it is relatively convenient and easier for the user since the GIS-enabled WEF nexus tool automatically exchanges information and analyses WEF nexus in space, without the need for manual preparation and transferring of information between the two systems. The latter mode of soft-linking or loose-coupling requires the user to manually prepare, manipulate, and transfer information between the geospatial tool and the WEF nexus tool, which is inconvenient, tedious, and prone to error by the user. GIS enhances finer spatial detailing of the WEF nexus profile in study areas (Eldrandaly, 2007; Ramos et al., 2019).

The minority of existing WEF nexus tools with geospatial capabilities, either by hard-linking or soft-linking, are presented in Table 5.

Table 5: WEF nexus tools with geospatial capabilities

Tool	Geospatial Features	Mode of GIS Integration
WEF Nexus Discovery Map (1)	Base map and hosting through ArcGIS	Hard-linked
ITEEM (3)	Spatial input datasets	Soft-linked
MAXUS (7)	Pre-processing of input datasets	Soft-linked
NEST (14)	Spatial input datasets	Soft-linked
WEF Nexus Index (16)	Global base map	Hard-linked
GREAT for FEW (18)	Base map and input datasets as spatial maps	Hard-linked
Daily Model (23)	Spatial input datasets and satellite-based climatic products	Soft-linked
DAFNE (24)	Spatial input datasets, Geoportal with a dynamic, customizable interactive web map by Web GIS and a customized additional "marker" layer	Hard-linked
SIM4NEXUS (25)	GIS layers for dams' location; GIS layers for digital elevation model	Hard-linked
Q-Nexus (30)	Base map	Hard-linked
PRIMA (38)	Spatial input datasets	Soft-linked
CLEWs (42)	Spatial input datasets	Soft-linked
WEAP-LEAP (43)	Thematic maps (land use), maps of basin	Hard-linked
Foreseer (44)	Spatial input datasets	Soft-linked
MuSIASEM (46)	Spatial input datasets	Soft-linked

Integration of GIS and WEF nexus tool should collectively accomplish pre-processing, spatial analysis, mapping and visualization, regardless of the integration arrangements of the two systems or sub-systems.

Existing WEF nexus tools with geospatial capabilities show that soft-linked WEF nexus tools and geospatial features use pre-processing, spatial input datasets, thematic layers, and post-processing. In modular soft-linked integration of the WEF nexus tool and GIS capabilities, the user performs geospatial tasks manually, as shown in Figure 10.

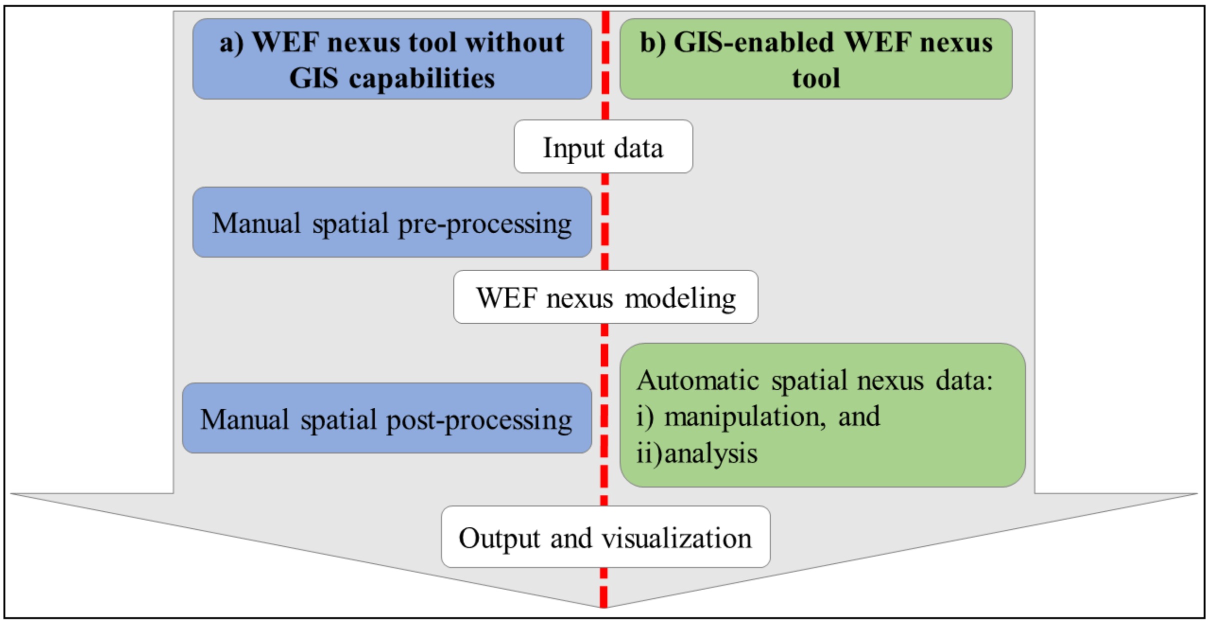

Figure 10: Difference in spatial WEF nexus analysis using a typical (a) left side – WEF nexus tool without GIS integration, and (b) right side – GIS-enabled hard-linked WEF nexus tool after (Burger, 2018; Burger and Abraham, 2020)

In this modular integration arrangement, the geospatial data may include land use, administrative boundaries, basins, sub-basins, climate change, socioeconomics variables, and WEF nexus variables (Vinca et al., 2020). Other spatial data that may need pre-processing include existing infrastructure, terrain, environmental policy, availability of natural resources, technology-specific siting suitability criteria, land use, land cover, and economic analyses of grid interconnection costs and locational marginal prices (SEI, 2012; Kraucunas et al., 2015).

Hard-linked GIS-enabled WEF nexus tools (Figure 10) depict that common techniques for this integration arrangement include the use of Web GIS, base maps, geodatabases and geoportals. The hard-linked integration allows for flexible web hosting of the tool, locating case study areas, real-time interaction, mapping, and visualizing spatial distributions of WEF nexus (Lin et al., 2019; Simpson et al., 2022; Arenas et al., 2021). Other benefits include storing, integrating, and sharing project GIS datasets (Melenhorst et al., 2018). Thus, geospatial capabilities in WEF nexus tools make it possible to effectively locate suitable sites, and quantify spatial WEF requirements, supply, budgets and footprints.

Therefore, there is great potential for comprehensive WEF nexus analysis and characterization if more of the reviewed existing WEF nexus tools could be equipped with geospatial capabilities, especially the user-friendly hard-linked integration. This tight coupling allows for automated exchange of information within the integrated system of the GIS-enabled WEF nexus tool, thus making it more convenient and easily applicable. This integration method removes the need for extra commitment in GIS training, data preparation and processing that comes with soft-linked integration of WEF nexus tools and GIS capabilities.

2.5.7 WEF Tools in Practice

The frequency of case studies for WEF nexus studies can be essential evidence of the practical applicability of the applied tools, especially if various authors applied the tools in different locations and conditions.

A majority (≈ 61%) of the existing 46 WEF nexus tools have been used in a few case studies between one to three applications (Figure 11 and Appendix 1).

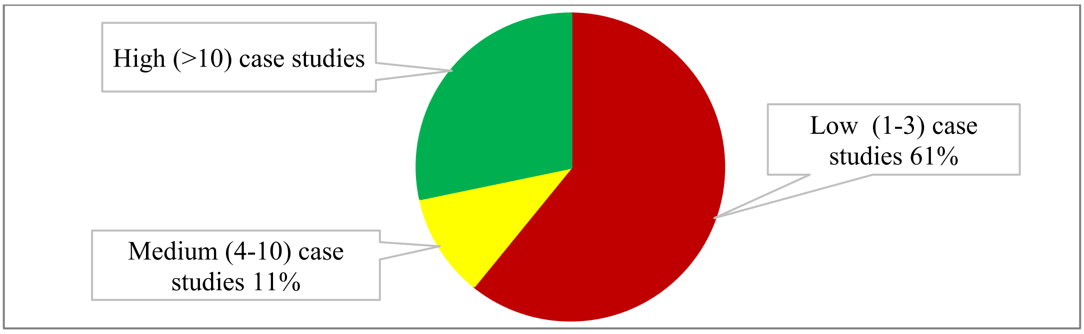

Figure 11: WEF tools in case studies

Despite showing great potential, most of these tools, including GREAT for FEW and DAFNE, were only applied by their developers in the original case studies for which they were developed. Interestingly, some tools that scored medium to high in the frequency of case studies were used in multiple areas by their developers only, with few case studies or none by other authors outside the development team. Such tools include the Back Propagation neural networks-DEcision Making Trial and Evaluation Laboratory-Game Theory Combination Weight (BP-DEMATEL-GTCW (2)) and System Dynamics Water-Food-Energy (SD-WFE (11)) applied in various locations in China (Chen and Chen, 2021) and Iran (Ravar et al., 2020), respectively. The lack of popularity in use can be linked to the fact that they are unavailable such that interested users cannot easily access most of the tools, as evidenced in Table 6 and Appendix 1, wherein a significant number of the widely used tools are readily available for users.

Table 6: WEF nexus tools, ready availability and their case studies

Low (1-3) Case Studies		**Medium (4-10) Case Studies**		**High (>10) Case Studies**	
Available	**Unavailable**	**Available**	**Unavailable**	**Available**	**Unavailable**
6	21	2	3	10	4
ITEEM (3); WEF-Sask (4); CALFEWS (5); WEF Nexus SD (8); FPC (9); WEF-P (10); WEST (12); MIFCP-WEFN (13); NEST (14); integrative analytical model for the WEF nexus (15); AWEFSM (17); GREAT for FEW (18); EPAT (19); WHAT-IF (20); K-WEFS (21); WEFSiM (22); Daily (23); DAFNE (24); UCEC (26); ABM-SWAT (27); WEF (29); NexSym (31); WEFO (32); SEWEM (33); BRAHEMO (34); IBMR-MY (35); Nexus Webs (41)		**Q-Nexus (30)**; **WEF Nexus Tool 2.0 (37)**; PRIMA (38); EWF Nexus (39); WEF Nexus Assessment 1.0 (40)		**WEF Nexus Discovery Map (1)**; BP-DEMATEL-GTCW (2); **NeFEW (6)**; MAXUS (7); SD-WFE (11); **WEF Nexus Index (16)**; **SIM4NEXUS (25)**; **Nexus Game (28)**; **Pardee RAND WEF Security Index (36)**; **CLEWs (42)**; **WEAP-LEAP (43)**; Foreseer (44); **ANEMI (45)**; **MuSIASEM (46)**	

Bold: readily available

Thus, the widespread use of WEF nexus tools must be promoted by availing them in the public domain, where they can be accessed without hassles. This regular use by different authors in different locations (i.e. different countries) and conditions can provide the feedback necessary for independent validation, further enhancing and improving tools.

2.6 Limitations of Review

This study adapted a systematic review that sought to systematically search for, appraise, and synthesise research evidence based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. One weakness of systematic reviews is excluding some literature by restricting the search and inclusion criteria. However, the PRISMA protocol in systematic reviews is still highly regarded in scientific research because of the transparency in reporting its methods, which allows for repeatability of the process and reproducibility of the results.

We deliberately chose not to contact the authors and developers of WEF nexus tools, who could have provided more details to answer the study questions. However, this was intentional to get the real picture of WEF nexus tools in the public literature and the web domain. This was to ascertain what is known and unknown as represented by the available information, whether in its sufficiency or insufficiency. The focus on named tools may have excluded some anonymous and general tools whose inclusion in this study would be difficult without unique identities. Conceptual frameworks and approaches without uniquely identified and tangible tools were also excluded from the study.

Similarly, tools whose development was proposed or still in progress, such as the Sustainable Development (SD) Calculator (Mosalam and El-Barad, 2020), were left out due to their incompleteness in development and application. As the water-energy-food-everything (WEF-e) system mentioned by Saundry and Ruddell (2020), the WEF nexus can be flexibly expanded to include several other dimensions such as economy, health, environment, nutrition, politics, climate, and land with the risk of complexity and dimensionality. However, our focus was on the first three dimensions of water, energy and food, such that our study focused on tools and models that capture the interlinkages of at least these three basic dimensions of the WEF nexus. However, investigating the actual nature and number of dimensions characterized by the individual WEF nexus tools was outside our scope and is a subject for further study.

2.7 Conclusion

Published literature reports a cumulative abundance of at least 46 uniquely identified tools dedicated to the WEF nexus, of which most of them are unreachable to the public. Thus, developers must avail their WEF nexus tools through promotion and dissemination, especially through open deployment on the public web domain, so that the tools can be rigorously tested and applied. For example, the web addresses for WEF nexus tools with dead links (e.g. Foreseer (44) and PRIMA (38)) need to be updated and disseminated. Public availability of WEF nexus tools could save time, costs, and human resources since tools can be freely used or customized instead of unnecessarily developing new tools from scratch every time a study is carried out. This can go a long way in facilitating the translation of WEF nexus theory to practice through nexus-friendly policy- and decision-making processes.

For enhanced user experience by a wide range of users, developers should strive to develop and deploy WEF nexus tools in a convenient, compatible, and friendly format. Preferable formats include desktop applications, web-based applications, and serious games with user-friendly GUIs. Serious games educate and build capacity on WEF nexus principles and practices, while the multi-player mode enhances the safe interaction of individuals with each other and the WEF nexus dynamics and scenarios.

Developers should consider transferability and scalability for wide utility in different scales, uses, and users when improving existing tools and developing new tools. This would ensure the utility of the WEF nexus tools under various geographic scopes, scales, and conditions without fundamentally changing their structure. WEF nexus tools should be flexible and adaptable, only requiring new, specific location-adapted inputs and data. WEF nexus tools and models should be developed on-demand as requested and inspired by potential clients (users). Thus, developers need to engage and collaborate with the target users in the process to satisfy the users' needs, expectations, and requirements. This user-driven design and development of WEF nexus tools are critical to enhancing user experience and ensuring the applicability of the developed tools.

There is a critical mismatch between the WEF nexus tools without geospatial capabilities and the inherently dynamic nature of WEF resources whose nexus they are supposed to quantify, analyse, and visualize. Thus, developers need to seriously consider GIS integration in designing and developing WEF nexus tools.

Most of the existing WEF nexus tools lack popularity in wide applications, and this can be partly attributed to them not being readily available. A majority have been used in a few case studies, mostly by their developers in the original case studies for which they were developed and tested. These tools can be used and assessed for applicability in different locations and conditions by their ready availability. The free availability of WEF nexus tools ensures broader chances of engagement, especially for users without adequate resources to procure costly modelling software in developing countries.

2.7.1 Coupling GIS and Integrative Analytical WEF nexus model

The techniques for coupling GIS to WEF nexus models include integrating (hard-linking) base maps or using (soft-linking) input thematic layers prepared by off-the-shelf GIS tools for geospatial analysis for pre- and post-processing. The first option is automatic and user-friendly than the second option, which is cumbersome and prone to errors. The use of base maps also renders the WEF nexus tool with spatial data handling capabilities. A wide range of base maps are available as open source. Therefore, we opted to couple GIS to the integrative analytical model for the WEF nexus by hard-linking with open-source base maps to reduce the model's cost of development and implementation. Additionally, it is easier and simpler for both the developers and users of the model to use open-source base maps, which automatically exchange information between the WEF nexus model component and the GIS, as compared to thematic layers and commercial GIS products whose manual transfer of information between WEF nexus model and GIS tool requires an extra commitment for training, data preparation and processing.

CHAPTER 3 RESEARCH METHODOLOGY

The detailed methodology for systematically reviewing published literature by PRISMA protocol for key characteristics of existing WEF nexus tools was presented in Chapter 2. This section presents the findings from the systematic review partly motivated the desired abilities in the iWEF model governing equations.

Despite the mention of many WEF nexus tools that attempt to capture the linkages between the three sectors of the nexus in literature, they are fraught with various deficiencies. A majority of them are unavailable in the public domain. Some are difficult to use without a proper GUI, an obstacle to non-specialists with no programming or coding knowledge. Some cannot analyse, model, or simulate the WEF nexus because they are just online information databases. Most of the tools focus on large scales than the local scales where the actual implementation of technical or policy solutions occurs and where benefits or impacts are directly realised and felt (Martinez-Hernandez et al., 2017). Some tools are area-specific, with limited applicability in other areas. Some lack important features for geospatial mapping, analysis and visualization. Some tools were and can be soft-linked to GIS through manual exchange and transfer of information between the two systems, which is inconvenient, time-consuming, and difficult for the user because they have to prepare the data into compatible formats. However, in a minority of the tools, the most common technique for coupling GIS to WEF nexus tools is the hard-linking method by incorporating a base map within the tool. Base maps are used as foundation layers to support a range of web maps or web mapping applications. The applicable base maps include those available in ArcGIS Online, Google Maps, OpenGIS and OpenStreetMap.

Therefore, there is great potential for comprehensive WEF nexus analysis if some of the reviewed tools can be available publicly on the internet, with geospatial mapping, analysis and visualisation capabilities and a user-friendly GUI. WEF nexus tools need to be applicable at a local scale for tailoring appropriate solutions for local conditions that utilize and take advantage of synergistic techno-ecological interactions.

3.1 The Integrative Analytical Model for the WEF Nexus

The MS Excel spreadsheet based integrative analytical model for the WEF nexus was originally developed by Nhamo et al. (2020a) for establishing quantitative relationships among WEF nexus sectors to indicate resource utilisation and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention. To facilitate WEF nexus performance assessment, monitoring and evaluation, the integrative analytical model for the WEF nexus (Nhamo et al., 2020a) holistically evaluates synergies and trade-offs to improve efficiency and productivity in resource use and management for sustainable development. Thus, the web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical model (iWEF) builds on the existing MS Excel-based Analytic

Hierarchy Process (AHP)-based integrative WEF nexus analytical model developed by Nhamo et al. (2020a,b).

After identifying and defining relevant WEF sustainability indicators, Nhamo et al. (2020a) developed a methodology to compute composite indices. The key input data for iWEF modelling are the six WEF sustainability indicators, per annum, including water availability (m^3/capita), water productivity (\$/m^3), energy accessibility (%), energy productivity (MJ/GDP), food self-sufficiency (%) and cereal productivity (kg/ha). These indicators are compared pairwise in a pairwise comparison matrix (PCM) based on expert opinion/advice, literature, or recognized databases (e.g. national statistics, World Bank, Aquastat, etc.) that can provide the baseline to establish the numerical relationship among indicators (Mabhaudhi et al., 2019; Nhamo et al., 2020a,b). Water availability is the proportion of available freshwater resources per capita, which estimates the total available freshwater water resources per person. Water productivity is the proportion of crops produced per unit of water used, which measures the output from an agricultural system in relation to the water it consumes. Energy accessibility is the proportion of the population with access to electricity, expressed as a percentage (%) of the total population. Energy productivity is synonymous with energy intensity, which is the energy supplied to the economy per unit value of economic output. Food self-sufficiency is the percentage (%) of individuals in the population, out of the total population, who have experienced food insecurity at moderate or severe levels during the reference year. Cereal productivity is the proportion of sustainable agricultural production per unit area (Nhamo et al., 2020a).

3.2 Conceptual Model for iWEF

A conceptual model is a non-quantitative representation of a system showing the system components and their interactions, usually developed before selecting or developing the quantitative model (Loucks and van Beek, 2017). The conceptual model of iWEF is shown in Figure 12 to be founded on the (AHP) multi-criteria decision making (MCDM) framework, which consists of the goal, indicators and pillars. The goal constitutes the objective to analyse the quantitative and spatial dynamics of the WEF nexus. The six indicators speak to the security of the three WEF pillars (water, energy and food), namely water availability (m^3/capita), water productivity (\$/m^3), energy accessibility (%), energy productivity (MJ/GDP), food self-sufficiency (%) and cereal productivity (kg/ha). These six indicators were defined in Section 3.1 and how they are gathered. Thus, these six indictors are manipulated by the AHP technique into normalised indices which are then integrated into the WEF nexus index, as explained in Section 3.1.

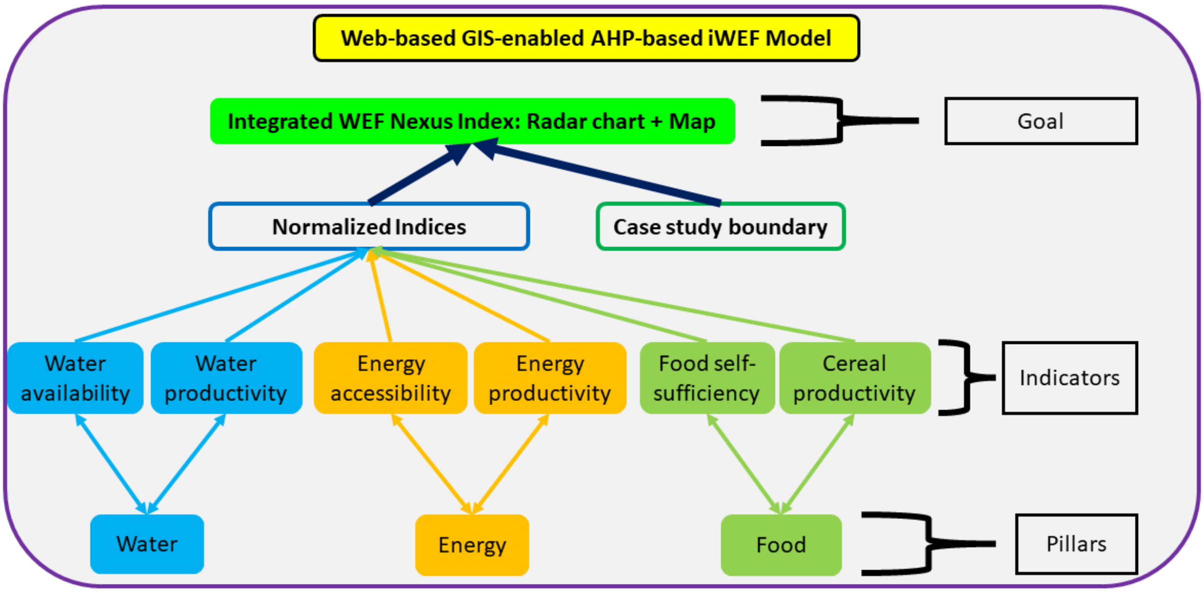

Figure 12: Conceptual model of iWEF

3.3 Mathematical (quantitative) model for iWEF

A mathematical model is a quantified conceptual model expressed in mathematical terms. It consists of the model's equations, typically including variables whose values are unknown and can vary and parameters whose values are assumed known (Loucks and van Beek, 2017). This section presents the mathematical models for iWEF to determine the consistency of the pairwise comparison matrix and the integrated WEF nexus index.

3.3.1 Determining the consistency of the pairwise comparison matrix

The iWEF tool integrates the six WEF indicators through the Analytic Hierarchy Process (AHP) multi-criteria decision-making (MCDM) approach (Brunelli, 2015) by normalising WEF indicators data to determine composite indices used to compute the weighted average WEF nexus index. According to Saaty (1987), the AHP is a theory of measurement for deriving ratio scales from both discrete and continuous paired comparisons to set priorities and make the best decisions. The AHP comparison matrix is determined by comparing two indicators at a time using Saaty's scale, which ranges between 1/9 and nine, as indicated in Table 7 (Saaty, 1987).

Table 7: Saaty's scale of relative importance for pairwise comparisons in an AHP

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Element *a* and *b* contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour element *a* over *b*
5	Essential or strong importance	Experience and judgment strongly favour element *a* over *b*
7	Very strong or demonstrated importance	Element *a* is favoured very strongly over *b*; its dominance is demonstrated in practice
9	Extreme or absolute importance	The evidence favouring element *a* over *b* is of the highest possible order of affirmation
2 (weak), 4 (moderate plus), 6 (strong plus), 8 (very, very strong), 1/2, 1/4, 1/6, 1/8	Intermediate values between the two adjacent judgments	When compromise is needed. For example, 2 can be used for the intermediate value between 1 and 3
1/3	Moderately less important	
1/5	Strongly less important	
1/7	Very strongly less important	
1/9	Extremely less important	
Reciprocals of above nonzero	If *a* has one of the above nonzero numbers assigned to it when compared with *b*, then *b* has the reciprocal value when compared with *a*	A reasonable assumption

Source: Saaty and Vargas (2012)

Based on the AHP method, the iWEF model computes the consistency ratio (CR), which measures the randomness and consistency of the pairwise judgements. The CR value is calculated as (Mu and Pereyra-Rojas, 2017):

$CR = \frac{CI}{RI}$ (Equation 1)

where: CI is the consistency index, RI is the random index, the average of the resulting consistency index depending on the order *n* of the matrix given by Saaty and Vargas (2012) (Table 8).

Table 8: Average random consistency index (RI)

N	1	2	3	4	5	6	7	8	9
Random consistency index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45

Source: (Saaty and Vargas, 2012)

CI is calculated as:

$CI = \frac{\lambda_{max} - n}{n-1}$ (Equation 2)

where: λ_{max} is the principal or maximum eigenvalue calculated by averaging the value of the consistency vector, Cv_{ij}, as follows:

$\lambda_{max} = \sum_{i=1}^{n} Cv_{ij}$ (Equation 3)

where: Cv_{ij} is calculated by multiplying the pairwise comparison matrix (C_{ij}) by the weights vector and then dividing the dividing the weighted sum vector with criterion weight (W_{ij}) (Teknomo, 2006; Vargas, 2010a; Vargas, 2010b; Bunruamkaew, 2012; Mu and Pereyra-Rojas, 2017) as:

$$Cv_{ij} = \frac{1}{W_{ij}} \sum_{i,j=1}^{n} C_{ij} W_{ij} \qquad \text{(Equation 4)}$$

According to Saaty and Vargas (2012), a value of less than 0.1 or 10% is acceptable for the CR, while a higher value is unacceptable and implies inconsistency in the pairwise comparison judgements.

3.3.2 Calculation and normalisation of indices

The AHP computes the indices for the indicators by taking the eigenvector corresponding to the largest eigenvalue of the matrix and then normalising the sum of the components (Nhamo et al., 2020a). The eigenvalue method synthesises a pairwise comparison matrix *A*, to obtain a priority weight vector for several decision criteria and alternatives. Here an eigenvector of matrix *A* is used for the priority weight vector. The priority weight vector is set to the right principal eigenvector w of the pairwise comparison matrix A in the eigenvector method. Therefore, the eigenvector method is to find the maximum value λ and its corresponding vector *w* such that (Saaty, 1990):

$$Aw = \lambda w \qquad \text{(Equation 5)}$$

The overall importance of each indicator is then determined. The matrix, *A*, of n criteria, is determined using Saaty's scaling ratios, in the order (*n x n*) (Saaty, 1990). *A* is a matrix with elements a_{ji}. The matrix's reciprocity is expressed as:

$$a_{ij} = \frac{1}{a_{ji}} \qquad \text{(Equation 6)}$$

After generating this matrix, it is then normalized as a matrix *B*, in which *B* is the normalized matrix of *A*, with elements b_{ji} and expressed as:

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ji}} \qquad \text{(Equation 7)}$$

Each weight value w_i is computed as:

$$w_i = \frac{\sum_{j=1}^{n} b_{ji}}{\sum_{i=1}^{n} b_{ji}},\ i, j = 1,2,3, \dots, n \qquad \text{(Equation 8)}$$

The iWEF model determines the integrated WEF nexus as a weighted average whose value ranges from zero to one and can be interpreted on its level or class of sustainability (Table 9) (Nhamo et al., 2020a). The value represents the overall performance of resource development, utilisation, and management as seen together (Nhamo et al., 2020a).

Table 9: WEF nexus indices performance classification categories

Index	Category and Interpretation			
	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
WEF nexus composite index	0-0.09	0.1-0.2	0.3-0.6	0.7-1

Source: Nhamo et al. (2020a)

3.4 Development of the iWEF Web-based and GIS-linked Tool

In its original MS Excel format, it was used to assess the WEF nexus at regional (southern Africa) (Mabhaudhi et al., 2019), national (South Africa) (Nhamo et al., 2020a) and local municipality (Sakhisizwe Local Municipality, South Africa) (Nhamo et al., 2020b) scale case studies. These previous applications concluded that the developed integrative WEF nexus analytical model is a decision support tool that indicates and exposes priority areas for intervention. However, there is room for improvement in web accessibility and GIS integration.

The iWEF model was developed using a conventional model and web building tools, and integrated with GIS to become a web-based WEF nexus model equipped with geospatial capabilities to provide quantitative and qualitative spatial information of the WEF nexus from a bird's eye view.

Thus, the current work rendered the MS Excel-based tool into an advanced and innovative web-based and GIS-enabled WEF nexus model (iWEF) through programming and web development. We adopted the computational equations (Section 3.1), which we converted to algorithms, and then added equations for computing the CR and GIS integration. The procedures followed in developing iWEF are elaborated in the succeeding sections.

3.5 Conclusion

The iWEF model was developed by further enhancing the tool by Nhamo et al. (2020a), specifically conversion into a web-based application integrated with GIS. The iWEF modelling tool applies the AHP MCDM technique on six indicators to establish interlinkages between WEF resources and inform decision- and policy-makers on WEF system sustainability. Its conceptual model consists of pillars and indicators of WEF security, and the ultimate goal is the integrated nexus index. The mathematical model for iWEF consists of computations for the CR, normalised indices and the integrative WEF nexus index.

CHAPTER 4 DEVELOPMENT AND TESTING OF THE WEB-BASED GIS-ENABLE WEF NEXUS TOOL

4.1 Brief on the Integrative WEF Nexus model (iWEF)

As alluded to, the original MS Excel-based version of iWEF lacked (i) ready availability to interested users in the public domain; (ii) a user-friendly GUI; (iii) computations for CR; and (iv) geospatial analytic capabilities. Thus, this work sought to address this gap by (i) upgrading the tool into a user-friendly web-based application; (ii) deploying it online as open-source; incorporating algorithms for calculating CR; and (iv) integrating it with GIS.

4.2 Web-Based GIS application needs and requirements

Most existing WEF nexus tools are not readily available to the intended users. Their functionality is also limited by the lack of geospatial analytic capabilities such as GIS. In an attempt to close these crucial gaps, the iWEF model (developed from the integrative analytical WEF nexus model by Nhamo et al. (2020b) is a web-based WEF nexus model equipped with geospatial capabilities to provide quantitative and qualitative spatial information on the WEF nexus from a bird's eye view. The motivation to locate the tool on the web is for easy, free and open-source availability, accessibility and usability by the public, who are the interested users in academia, research, managers and planners, and policy and decision-makers. iWEF harnesses the power of GIS to analyse, visualize and display spatial distributions of resources requirements, availability, distribution, utilization and management to assist decision-making for infrastructure investments, policy development, land use and spatial planning. Additional important needs and requirements to enhance the iWEF model's applicability include a user-friendly GUI, flexibility across multiple scales, and flexibility of input data. Thus, the iWEF model contributes to closing the gap between the WEF nexus theory and actual practice by supporting and informing the implementation of the WEF nexus approach.

4.3 Web-based GIS-enabled iWEF's revised functional expectations

To perform its required functions of automatic, simultaneous spatial WEF nexus analysis and visualisation, iWEF was expected to:

1. Allow users to feed WEF indicators inputs, pairwise comparison matrix and case study generic details (name, location/shapefile/boundaries);
2. Compute the CR value from provided inputs and accept input data if the CR value is less than 0.1; otherwise, return an "error" message that prompts the user to edit the input values if the CR value is above 0.1;
3. Compute composite indices from provided inputs;
4. Normalize the composite indices;
5. Compute the median of calculated indices;
6. Compute the weighted average index (the system's nexus) from calculated composite indices;
7. Display table of results (pairwise comparison matrix, normalized composite indices for individual indicators, and overall index);
8. Draw and display graphical results (spider diagram, WEF nexus map); and
9. Compare results for several case studies using spider diagrams and WEF nexus maps.

4.4 Web-based GIS-enabled iWEF mode of operation

To fulfil its functional expectations, the iWEF model consists of four components, namely (i) database, (ii) user interface, (iii) computation, and (iv) results; which work in harmony with the model's mode of operation (Figure 13).

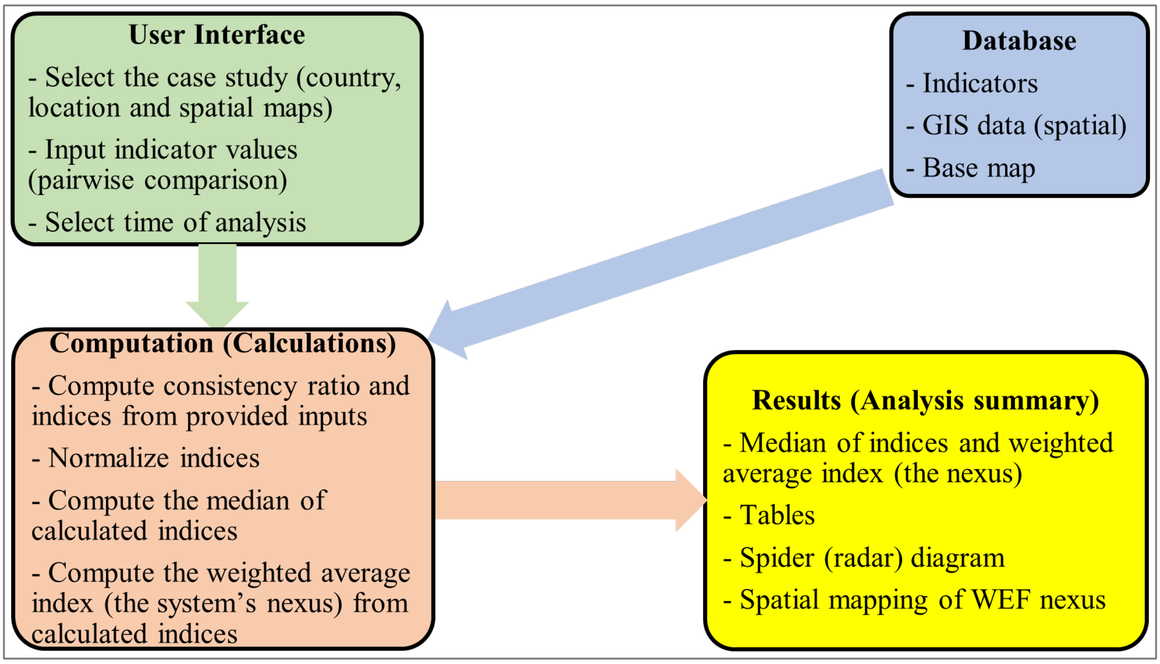

Figure 13: Mode of operation or operating procedure of iWEF

Generally, the GUI allows users to interact with the iWEF's database, which stores WEF nexus indicators data to be transformed by the computation module into useful results displayed as tables, graphs, and maps for interpretation and further analyses.

4.5 Web-based GIS-enabled iWEF development life-cycle – Modified Waterfall

Among the various application development life cycles, the chosen development life-cycle for iWEF was an adaptation of the Environmental Protection Agency (EPA, USA) modelling life-cycle (EPA, 2009) and the Modified Waterfall model (Conrad et al., 2016), allowing developers to return to a previous phase ideally confined to connecting steps (Figure 14).

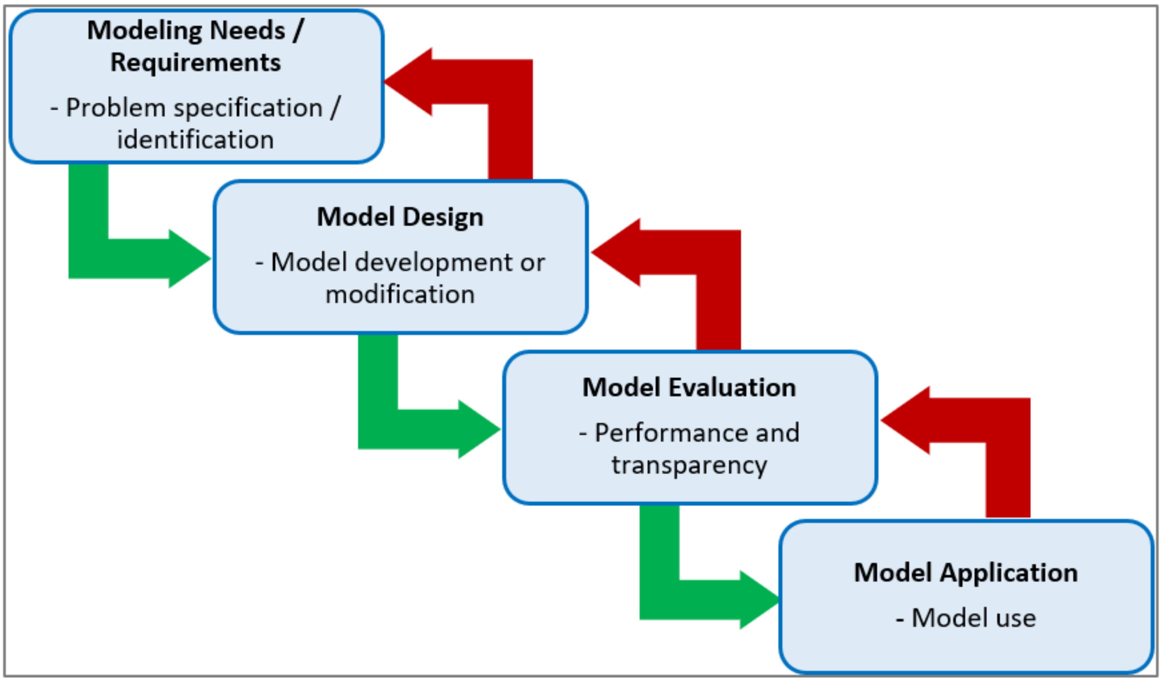

Figure 14: The Modified Waterfall model adapted to EPA's modelling life-cycle adapted from (EPA, 2009; Conrad et al., 2016)

The iWEF application was developed as guided by this nonlinear and bottom-up development life-cycle. It offered the possibility and flexibility of going back to the previous stage for correction, verification, validation and improvement. It was also useful for keeping the project's progress in order, straightforward, simple, and easy to understand and explain. To add, the Modified Waterfall life cycle model produced a stable product.

4.6 Web-based GIS-enabled iWEF development – Front end, back end and tools

The web-based and GIS-enabled iWEF model was developed for the two commonly tasks: the back-end and the front-end. Visual Studio Code[16] was used for writing codes, while Github[17] was used for version control, backup and spinning the server using Git.

The back-end is the specialized component of the iWEF model's application that is not directly accessed by the user, typically responsible for storing and manipulating data and ensuring that the client-side works. It will consist of three parts: (i) server, (i) visualization, and (iii) a spatial database. The back-end consists of the Python framework for web development, Django[18], and Dash-Plotly[19] as the Python framework[20] for data visualization.

[16] https://code.visualstudio.com/
[17] https://github.com/
[18] https://www.djangoproject.com/
[19] https://plotly.com/dash/
[20] https://www.python.org/

4.7 Web-based GIS-enabled iWEF development – Coupling GIS and iWEF model

The iWEF model was integrated into GIS by hard-linking to an open-source base map so that users can locate their case studies, and spatially analyse and visualize their results. Unlike soft-linking, which is cumbersome and prone to errors, hard-linked integration is automatic, simple and user-friendly in exchanging input/output information between the WEF nexus tool and GIS. The use of open-source base maps reduces the overall cost and time of developing and implementing the GIS-enabled WEF nexus model.

The iWEF was GIS-enabled through a 'hard-linked' GIS integration of the WEF nexus model with open-source base maps displayed on the front-end using the JavaScript library, Leaflet. Leaflet can be used with several plugins that provide open-source base maps. In addition, some editing geometries Leaflet plugins that contain functionalities for drawing and downloading boundaries and shapefiles of study studies. The display of the output graphs and maps of study area boundaries are handled using the Python framework for building analytic web applications, Dash, coupled with Plotly, a python library for developing online data analytics and visualization tools. The combination of Dash and Plotly, commonly known as Dash-Plotly, enables users to select interactively different study areas under investigation, display and compare their WEF nexus results.

4.8 Web-based GIS-enabled iWEF development – Database

The database technologies included PostgreSQL database management system and PostGIS. The PostgreSQL database[21] and its spatial extender, PostGIS, which adds spatial functionalities, are both Open Geospatial Consortium (OGC) Web Map Services standards-compliant and open-source. PostGIS[22] allows PostgreSQL to augment support for geographic objects, thus understanding coordinate systems, projections, and transformations (MacEachren et al., 2008).

The database was and will continue to be populated with the six WEF sectors nexus indicators and shapefiles. The database will also be continuously populated with existing shapefiles for major river basins, sub-basins, catchments, and administrative boundaries from internet archives and libraries. Functions of the base map include rendering geospatial capabilities to the iWEF model, such as locating case studies and mapping the WEF nexus. Functions for periodic updating of the database with new shapefiles at different scales will be included to capture any new shapefiles used by the users, curated/verified by the administrators and populated into the database. This will be done with the consent of the users through the use of a form created in Django.

[21] https://www.postgresql.org/
[22] https://postgis.net/

4.9 The computation module

The model's computation component consists of the codes and algorithms for governing equations for reciprocity of indicator values, calculating CR values, sums, weights, indices of indicators, and overall index (WEF nexus index) as the weighted average. Dash Plotly was used for visualizing the different outputs of the iWEF model (e.g. graphs, maps).

4.10 Web-based GIS-enabled iWEF development – The user interface

The second task was developing the front end, which includes the user interface. This is the screen for the program interface, including tabs for pages including 'Home', 'User Registration and Login', 'Data', 'Analysis' or 'Compute', 'Contact Us', 'Help', 'Logout' and other interaction screens. This serves as the point of interaction and control for the users with the iWEF model, allowing users to input their desired data and settings. Interface design determines the efficiency of interaction between the user and the system (Gupta and Malik, 2005).

The GUI and its component pages were designed using wireframing technology. A wireframe is a two-dimensional schematic illustration or blueprint image or set of images that displays the functional elements of an app interface, website or page, typically used for planning a site's structure, functionality, space allocation, prioritization of content, functionalities available, and intended behaviours[23]. The Balsamiq Wireframes[24] software was used to draw the wireframe of iWEF. The wireframes for the content of the iWEF model's interface include 'Home' (Figure 15), 'Data' (Figure 16), and 'Analysis' (Figure 17).

[23] https://www.usability.gov/how-to-and-tools/methods/wireframing.html
[24] https://balsamiq.com/

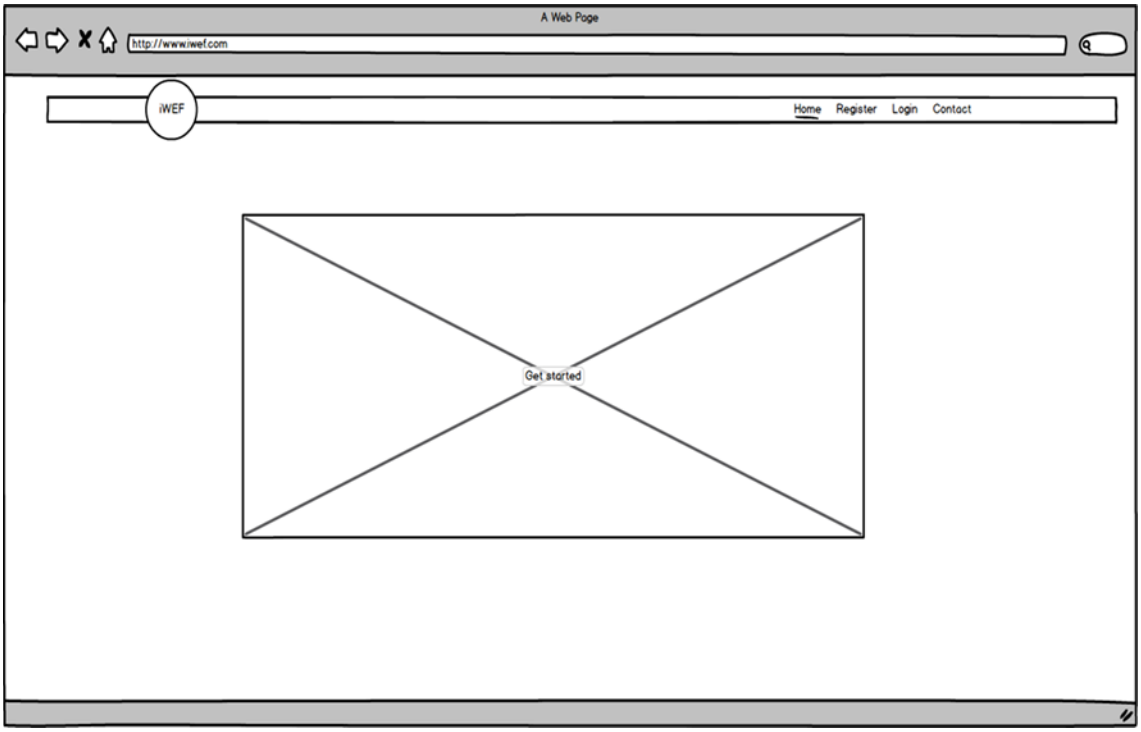

Figure 15: Wireframe for ‘Home’

The ‘Home’ page is the landing page for the iWEF model site where a user lands after they click on a link from any place on the web.

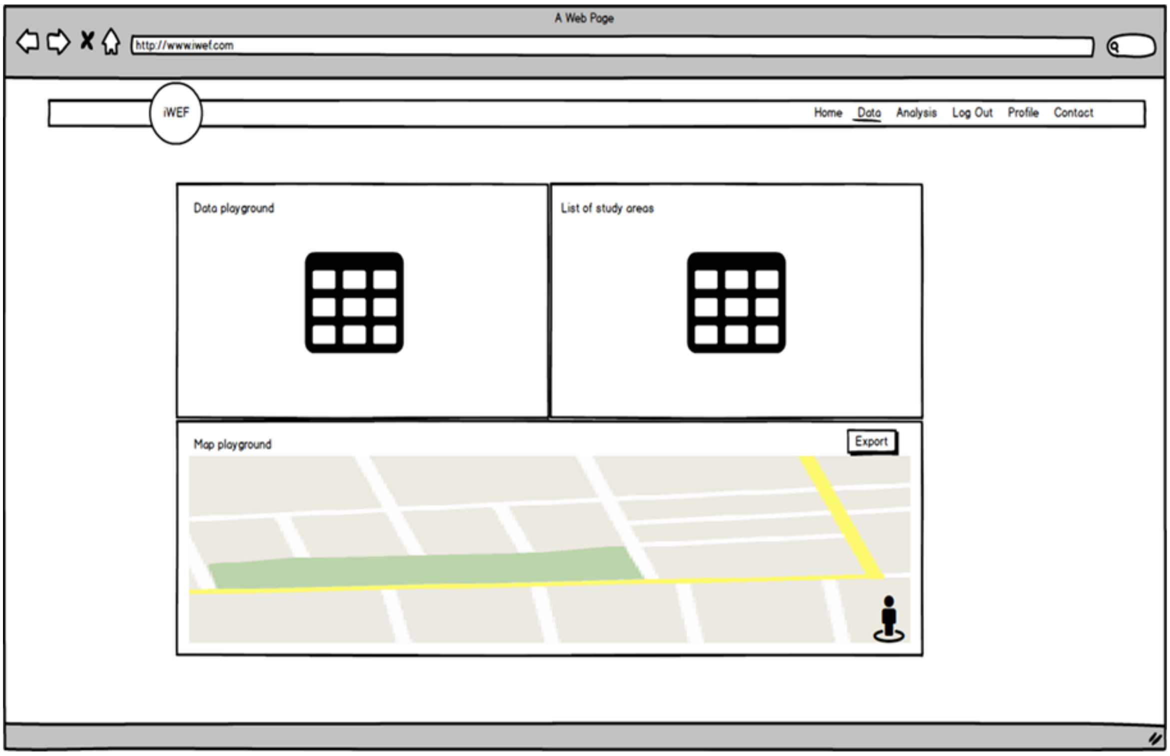

Figure 16: Wireframe for 'Data'

Accessible from the 'Home' page, the 'Data' page is where users feed their input data into the iWEF model.

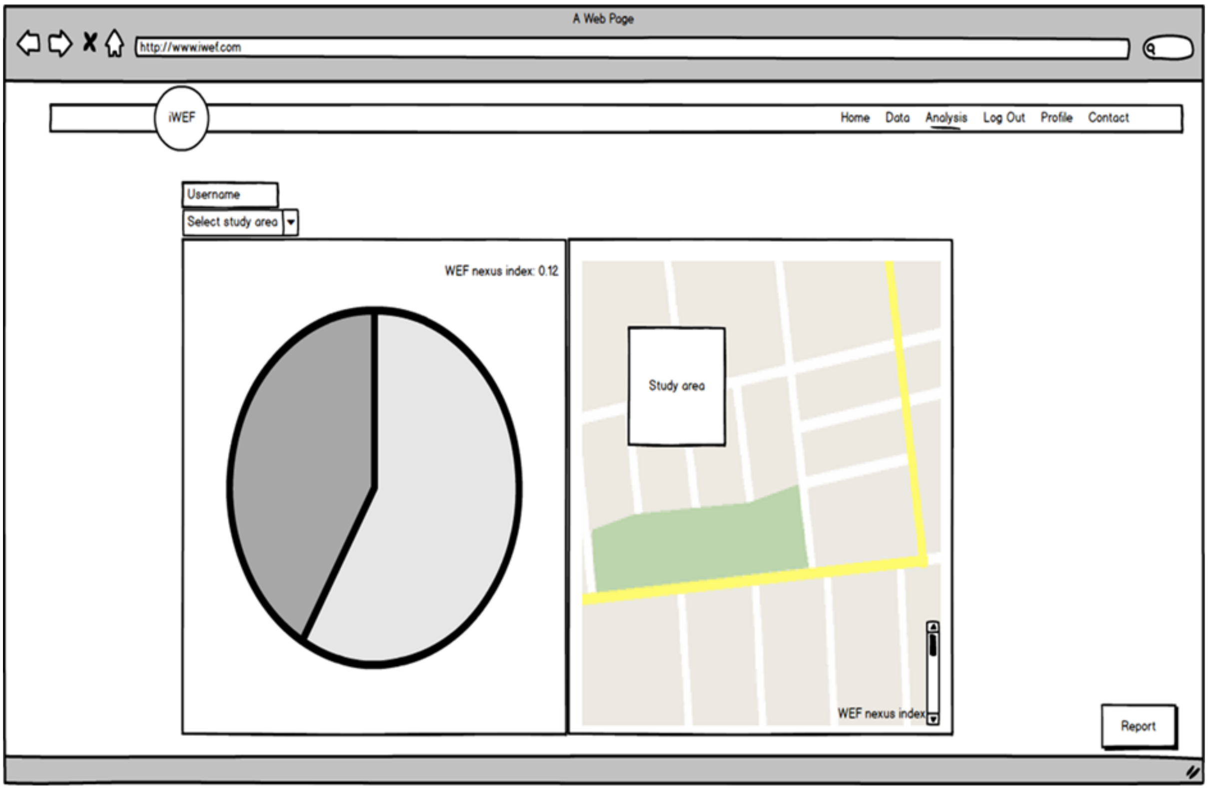

Figure 17: Wireframe for 'Analysis'

The 'Analysis' page is accessible from the 'Home' page and assists the user to perform computations that lead to the determination of the WEF nexus for their case study.

The 'Register' form is used to register a user into the application's system to be authenticated and allowed access. The registration form consists of input fields for username, email, password, password confirmation, and click tabs for register and home. The 'Login' form is where users enter their unique secure details (username or email and password) to access the system to edit their profile, use the tool, and visualise present and previous results. The 'Data Playground' form is used to capture indicator values by a user for their case study, using pairwise comparison values between one indicator of interest relative to the other five indicators at a time. The 'Map Playground' form is used to delineate the study location boundaries by a user for their case study. For the users' convenience, the user interface contains links to manuals, guides and instructions on how to feed input data, delineate a study area, compute, display and interpret results. This information is in the form of videos, manuals, guidelines, instructions, auto emails, pop-up screens and help functions. 'Contact Us' forms were also incorporated to capture and manage user feedback and enquiries.

4.11 Web-based GIS-enabled iWEF development – Output design

The output was designed for users to view information (processed data) stored in the system in the form of tables, graphs and maps. The final outputs include a weighted average index (the nexus), spider (radar) diagram showing WEF trade-offs and synergies (Flammini et al., 2014), and maps showing the spatial variation of the WEF nexus. The indicators table data interface is used to view and review information about a case study stored in the database. The spider graph also illustrates and compares sectors' sustainable or unsustainable management performance.

4.12 Web-based GIS-linked iWEF development – Web hosting iWEF

The iWEF model was deployed on the internet on a dedicated website with a secured domain name (https://iwef.app) after considering pertinent factors such as costs and the security and privacy of the tool and its users. To promote its applicability to prospective users, iWEF is accessible freely as an open-source web application.

4.13 Web-based GIS-linked iWEF development – Operating procedure

To operate iWEF, users are required to chronologically follow the steps presented in Figure 18, showing how iWEF will work from the users' perspective. By clicking the 'Help' tab, users can familiarize themselves with iWEF and learn how to use iWEF through instructions, guides, and preloaded sample data, analysis, and interpretation.

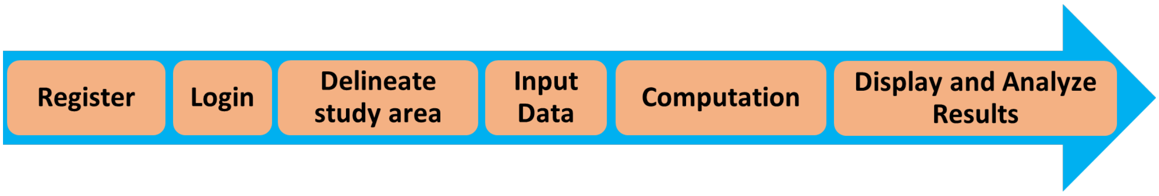

Figure 18: Application flowchart for the user

On visiting iWEF's web page, users will be prompted to register for a personal account with a unique username and password stored in the system database. These will be used as their unique identity whenever they access iWEF to locate their study area, feed input data, compute the WEF nexus, display, analyse, interpret, compare results, or retrieve previous case studies. After their session, the user can log out of their account tab. More details on how to easily and successfully use iWEF are provided step-wise in the detailed user manual in Appendix 2. Alternatively, users can watch the provided video tutorial.

4.14 Web-based GIS-linked iWEF in operation – Testing and trial runs

Testing iWEF involved running trials to ascertain the model's accuracy and reliability in computing the CR value and the WEF nexus index.

4.14.1 Browsers compatibility and screen resolutions

The iWEF model was successfully loaded and executed in Microsoft Edge (v99.0.1150.36), Google Chrome (v99.0.4844.51) and Mozilla Firefox (97.0.1). The model was also successfully loaded and executed on laptop and desktop computers and smartphones and tablets at good resolutions.

4.14.2 Testing iWEF model for CR value

Two pairwise comparison matrix datasets were randomly generated to test the accuracy of the iWEF model in calculating the CR value (i) within an acceptable range (less than 0.1 or 10%) and (ii) beyond the acceptable range (0.1 or 10% and above) (Teknomo, 2006; Vargas, 2010a; Vargas, 2010b; Bunruamkaew, 2012; Mu and Pereyra-Rojas, 2017). The typical inconsistent and inconsistent pairwise comparison judgment datasets are presented in Tables 10 and 11.

Table 10: A typical inconsistent pairwise comparison judgement dataset

Indicator Name	**Water availability**	**Water productivity**	**Energy accessibility**	**Energy productivity**	**Food self-sufficiency**	**Cereal productivity**
Water availability	1,00	1,00	1,00	0,33	0,33	1,00
Water productivity	1,00	1,00	3,00	5,00	1,00	1,00
Energy accessibility	1,00	0,33	1,00	3,00	0,20	0,33
Energy productivity	3,00	0,20	0,33	1,00	1,00	5,00
Food self-sufficiency	3,00	1,00	5,00	1,00	1,00	7,00
Cereal productivity	1,00	1,00	3,00	0,20	0,14	1,00

Table 11: A typical consistent pairwise comparison judgement dataset

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity
Water availability	1,00	1,00	1,00	0,33	0,33	1,00
Water productivity	1,00	1,00	3,00	1,00	1,00	1,00
Energy accessibility	1,00	0,33	1,00	0,33	0,20	0,33
Energy productivity	3,00	1,00	3,00	1,00	1,00	2,00
Food self-sufficiency	3,00	1,00	5,00	1,00	1,00	7,00
Cereal productivity	1,00	1,00	3,00	0,50	0,14	1,00

The two pairwise comparison matrices were tested in the iWEF model and the simple web-based AHP Priority Calculator (AHP Online System - AHP-OS)[25] by Goepel (2022). The results of CR values from both tools are presented in Table 12.

Table 12: Results from testing for CR value

Tool	CR Value	
	Inconsistent Dataset	*Consistent Dataset*
iWEF Model	0.31	0.07
AHP Online System (AHP-OS)	0.31	0.07

From Table 12, it is evident that the iWEF model is accurate and reliable in determining the CR value because its results were similar to those from the AHP Online System (AHP-OS). Thus, the iWEF model can reliably inform and guide users in ensuring the randomness and consistency of their pairwise comparison matrix judgements. This is crucial in the sound determination of WEF nexus indices representing WEF interconnections in their case studies.

4.14.3 Testing iWEF model for WEF nexus index

The initial version of the web-based and GIS-enabled iWEF model was tested with input from three previous case studies by the developers. The results were visually and quantitatively

[25] https://bpmsg.com/ahp/; https://github.com/bpmsg/ahp-os

compared with those from the original case studies in which the MS Excel-based tool was previously used.

Results between the two versions of the model were similar for the southern Africa regional case study by Mabhaudhi et al. (2019) for 2017, as illustrated in Figures 19-20, while Figure 21 showcases the extra strength of iWEF in spatial mapping and visualisation of the WEF nexus.

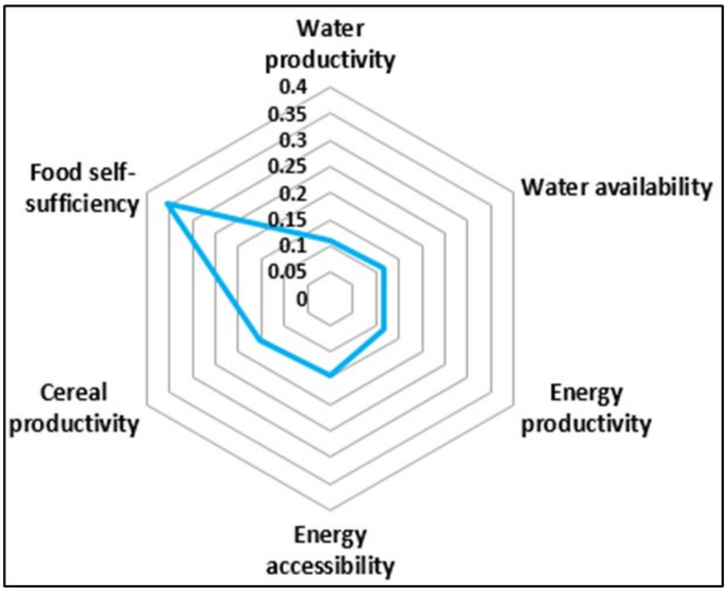

Figure 19: WEF nexus analysis results with value of 0.2 at regional scale for Southern Africa using the MS Excel-based tool (Mabhaudhi et al., 2019)

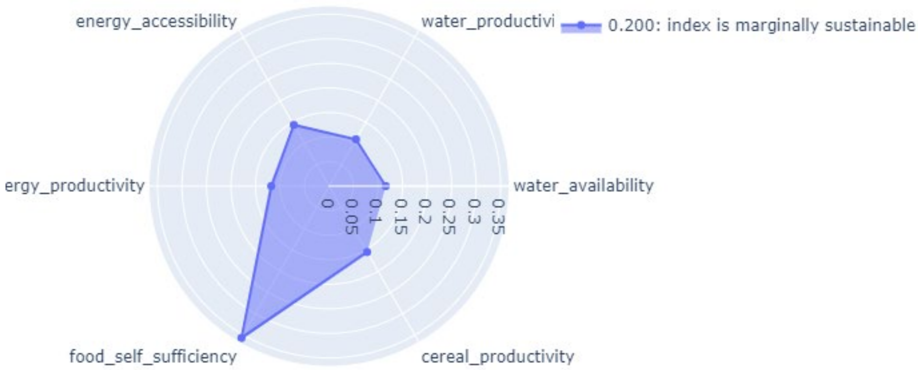

Figure 20: WEF nexus analysis results with value of 0.2 at regional scale for Southern Africa using the web-based iWEF tool.

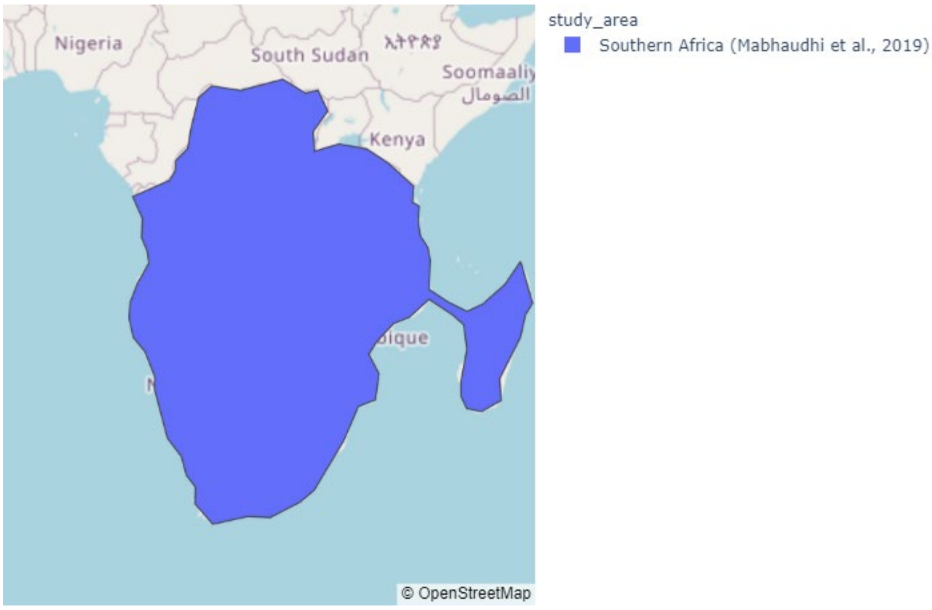

Figure 21: Results of spatial mapping of the WEF nexus by the iWEF tool at a regional scale (Southern Africa)

For the South African national case study by Nhamo et al. (2020a) for 2015, the MS Excel-based tool and the prototype of the web-based GIS-enabled iWEF model produced similar visual and quantitative results, as shown in Figures 22 and 23. Additionally, the iWEF model spatially characterised the WEF nexus (Figure 24).

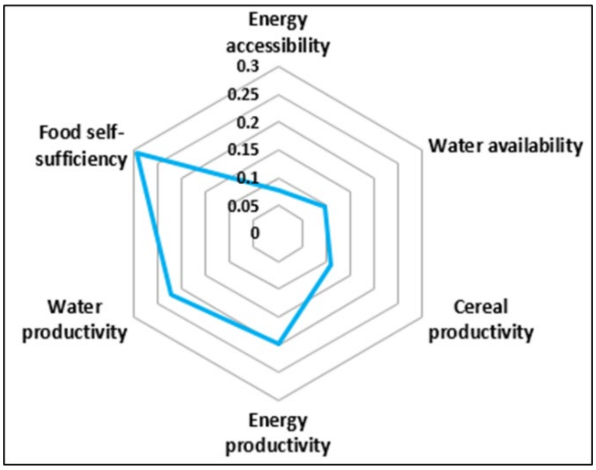

Figure 22: WEF nexus analysis results with value of 0.203 at national scale for South Africa using the MS Excel-based tool (Nhamo et al., 2020a)

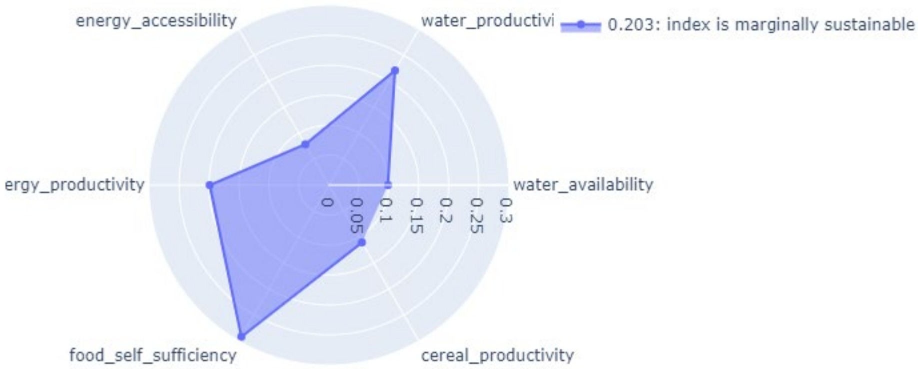

Figure 23: WEF nexus analysis results with value of 0.203 at national scale for South Africa using the iWEF model

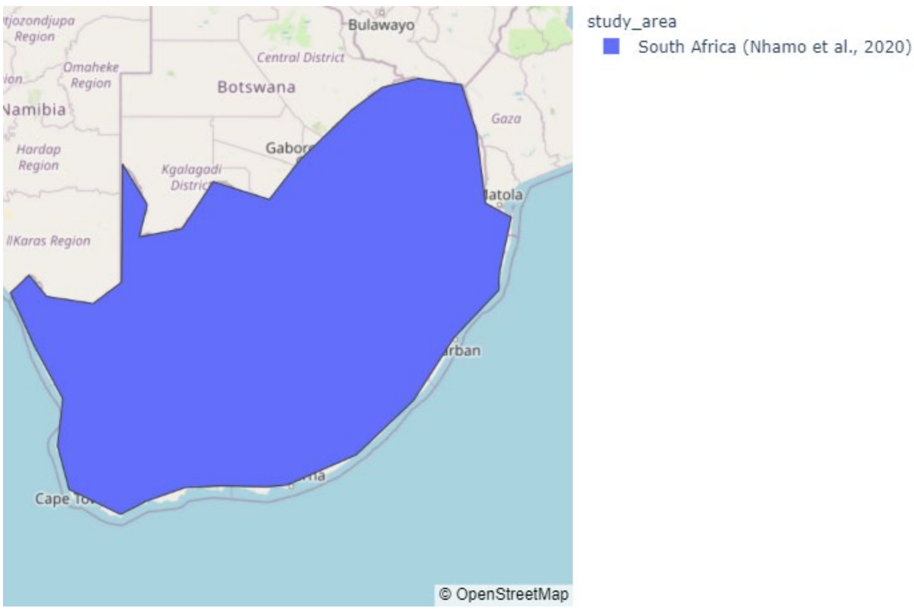

Figure 24: Results of spatial mapping of the WEF nexus using the iWEF model, at national scale (South Africa)

The MS Excel-based iWEF model and the web-based GIS-enabled iWEF model produced similar results for the local scale Sakhisizwe Local Municipality (South Africa) case study 2018 data by Nhamo et al. (2020b), as shown in Figures 25 and 26. To add, the iWEF model managed to spatially visualize the WEF nexus (Figure 27).

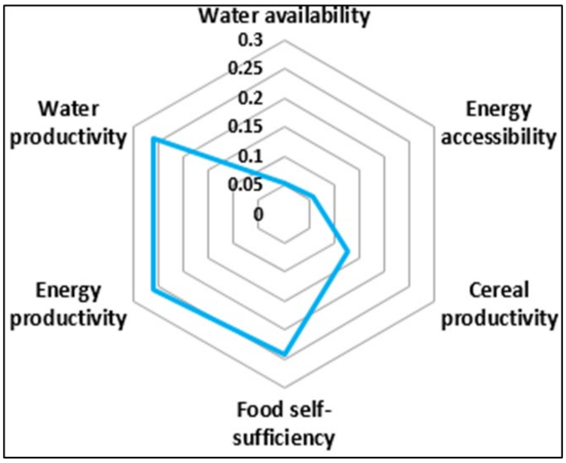

Figure 25: WEF nexus analysis results with a value of 0.208 at local municipal scale for Sakhisizwe Local Municipality (South Africa) using the MS Excel-based tool (Nhamo et al., 2020b)

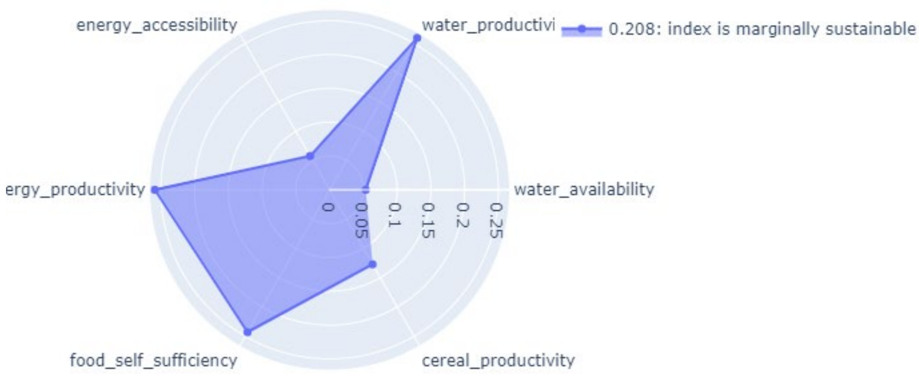

Figure 26: WEF nexus analysis results with a value of 0.208 at local municipal scale for Sakhisizwe Local Municipality (South Africa) using the iWEF tool

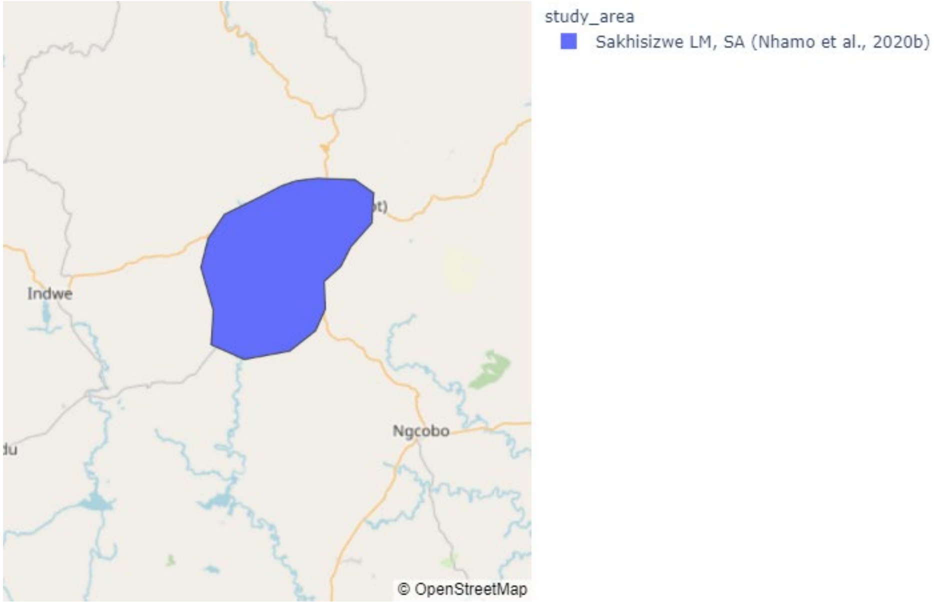

Figure 27: Results of spatial analysis of the WEF nexus at local municipal scale for Sakhisizwe Local Municipality (South Africa) using the iWEF model

From these instances of testing, verification and validation, it can be safely concluded that the web-based GIS-enabled iWEF model is accurate in computing and presenting the WEF nexus at multiple scales. Thus, iWEF can confidently be used in other case study areas of interest to characterise the WEF nexus.

4.15 Plans for analyses for at least two scales

The related WRC funded WEF nexus research project C2019/2020-00007 (From Theory to Practice: Developing a Case Study and Guidelines for Water-Energy-Food (WEF) Nexus Implementation in Southern Africa), intends to use the web-based and GIS-enabled iWEF model in analysing historical, current and future WEF nexus for implementing WEF nexus in their case studies in southern Africa. Thus, iWEF will be tested and validated through application in the catchment and municipal case studies in Zimbabwe and South Africa. The proposed case studies in Zimbabwe will be Mzingwane Catchment and Umzingwane District Municipality, while their South African counterparts will be Inkomati-Usuthu Water Management Area (WMA) and Ehlanzeni District Municipality, respectively. One of the case study areas for this collaboration and leveraging is briefly described in this section.

4.15.1 Inkomati-Usuthu WMA

Established in 2004 in terms of Section 78 of the National Water Act 36 of 1998 (NWA), the Inkomati-Usuthu WMA is located in Mpumalanga Province (South Africa) and falls under the Inkomati-Usuthu Catchment Management Area (IUCMA). It is situated in the north-eastern part of the Republic of South Africa (RSA) and borders Mozambique and the Kingdom of Eswatini. It forms part of an international river basin (Inco-Maputo) shared between South Africa and Mozambique. It covers 20987 km^2, and its main rivers include the Nwanedzi, Sabie-Sand, the Crocodile (East), Komati and Usuthu. The major dams include Nooitgedacht, Vygeboom, Da Gama, Witklip, Kwena, Driekoppies, Heyshope, Inyaka, Jericho, Klipkoppies, Longmere, Morgenstond, Primkop and Westoe. The Inkomati sub-catchment includes the Albert Luthuli, Emakhazeni, Umjindi, Mbombela, Thaba Chweu, Bushbuckridge and Nkomazi Local Municipalities. The Local Municipalities of Mkhondo and Albert Luthuli are within the Govan Mbeki District Municipality, the Local Municipalities of Nkomazi, Umjindi, Mbombela, Thaba Chweu, and Bushbuckridge are within the Ehlanzeni District Municipality, and Emakhazeni Local Municipality is within the Nkangala District Municipality. The Usuthu sub-catchment entirely falls under the Govan Mbeki District Municipality and encompasses the towns of Amsterdam and Piet Retief (DWA, 2012).

Historical climate data for 1960-2010 shows a spatially coherent reduction in (March-April-May) precipitation, 90^{th} percentile rainfall and rain days. Increased annual mean and 90^{th} percentile maximum and minimum temperatures are evident. Inkomati-Usuthu WMA is vulnerable to climate-induced shocks such as droughts. The El Nino-induced drought in 2015/16 severely affected water availability in the Inkomati-Usuthu WMA. Dams in the Crocodile and Sabie catchments had not recovered from this drought by 2019-2020. In the 2019-2020 hydrological year, the water availability situation in the Crocodile and Sabie/Sand catchments (Crocodile, Sabie and Sand rivers, tributaries, and dams) was still below normal when compared to previous hydrological years, due to total monthly rainfall received which was below the historical average. Ripple effects were felt in the water use sectors such as agriculture and power generation (DEA, 2013; IUCMA, 2019).

The total population in Inkomati-Usuthu WMA is approximately 2.8 million, at an annual growth of 1.61% (2016) (StatsSA, 2018). The Inkomati-Usuthu WMA is characterised by energy from coal and hydropower; mining of coal and other minerals; agricultural practices like sugarcane and macadamia farming; forestry practices for timber production; and a range of light industrial activities linked to these primary land-based productive activities (sugar mills, sawmills, furniture, food processing from sub-tropical fruits and nuts). Water use is shared between irrigation (31%), ecological reserve (23%), afforestation (21%), strategic (8%), cross border (6%), domestic (5%), alien vegetation (3%), transfers (2%) and industrial (1%) (2016). Hence agricultural water use claims the largest portion of 52% (IUCMA, 2020). According to StatsSA (2018), approximately 80% of households have access to safe drinking water. The prevalence of running out of money to buy food in the last 12 months is 23%, while 15% skipped a meal in the last 12 months (2016).

For renewable energy technologies, the Sappi Ngodwana Biomass Power Station is a 25 MW biomass (wood and paper mill biowaste)-fired thermal power plant under development by an independent power producer. It is in Ngodwana town in Ehlanzeni District. Busby Renewables Biomass Project is a planned 5 MW independent power plant fuelled by timber waste.

However, the project is still waiting for a financial close since 2015. The Inkomati-Usuthu WMA has good potential for new small-scale hydro development and is embedded in water transfer and gravity-fed systems (StatsSA, 2018).

Issues and challenges include inequitable distribution because of varied rainfall; water stress (quantity and quality) resulting in over-allocation before the reserve is implemented; inefficient use of certain areas; strategic water export, in the form of inter-basin transfers for Eskom and international obligations; and virtual water export in the form of exported products; uncoordinated poorly resourced land use planning and management have potentially negative impacts on terrestrial and aquatic systems; poor municipal waste (dumps, sewerage, storms water, etc.) management practices result in decreased water quality and fitness for use (IUCMA, 2020). Water pollution is caused by coal mining, industrial effluent from the tannery, untreated wastewater, wastewater irrigation, irrigation return flows, upstream wastewater, seepage, paper mill waste, over-abstraction, informal housing developments, poor sanitation (pit latrines) (IUCMA, 2020). There is constant competition for land between agriculture and mining in this province and between water for energy and water-for-food since coal mining activities occur within areas where high potential arable land is also located (Simpson et al., 2019).

There are ongoing WEF nexus research projects through partnership(s) of WRC, UKZN, International Water Management Institute (IWMI), ARC and IUCMA. Thus Inkomati-Usuthu WMA is a good testbed for testing, validating and applying the iWEF model in implementing WEF nexus due to the catchment's current WEF challenges, silo-based policy framework (legislation, plans, strategies), ongoing related projects with a different focus and available stakeholders and data sources.

4.16 Conclusion

iWEF harnesses the power of GIS to analyse and visualize/display spatial distributions of resources requirements, availability, distribution, utilization and management while presenting the spatial-temporal results to assist decision-making for infrastructure investments, policy development, land use and spatial planning. iWEF was GIS-enabled through a 'hard-linked' GIS integration of the WEF nexus model with open-source base maps that will be displayed on the front-end using the JavaScript library, Leaflet. Leaflet can be used with several plugins that provide open-source base maps. In addition, there are also some editing geometries Leaflet plugins that contain functionalities for drawing and downloading boundaries and shapefiles of study studies. The display of the output graphs and maps of study area boundaries are handled using the Python framework for building analytic web applications, Dash, which will be coupled with Plotly, a python library for developing online data analytics and visualization tools. Dash and Plotly, commonly known as dash-plotly, enables users to select interactively different study areas under investigation and display and compare their WEF nexus results. The web-based and GIS-enabled WEF nexus model is hosted online on the WebLeaflet, and Dash-Plotly, alongside the previously mentioned back-end and front-end technologies, is expected to significantly improve the capability of iWEF.

Key outputs in iWEF include a spider graph (radar chart or sustainability polygon) of normalised indices and maps. The shape of the radar chart illustrates WEF nexus indicator performance and inter-relationships, providing a synopsis of the level of interactions, interdependencies and inter-connectedness among WEF nexus sectors, whose management is perceived as either sustainable or unsustainable. The maps show the WEF nexus spatial distribution in the locations of interest, thus highlighting the hotspots and champions. The iWEF model can display radar charts and map results for multiple case studies, allowing scenario planning and analysis.

CHAPTER 5 DISSEMINATION AND UPTAKE OF THE WEB-BASED GIS-ENABLED WEF NEXUS TOOL

The main objective of iWEF dissemination is to promote the uptake of the iWEF model to particular communities or target audiences. This section presents the steps that were and are still being taken to disseminate the iWEF model.

5.1 Collaborations and Liaisons

Leveraging on and in collaboration with the ongoing Water Research Commission funded project C2019/2020-00007 (FROM THEORY TO PRACTICE: DEVELOPING A CASE STUDY AND GUIDELINES FOR WATER-ENERGY-FOOD (WEF) NEXUS IMPLEMENTATION IN SOUTHERN AFRICA), the iWEF model will be practically applied with stakeholder consultation in real case studies in South Africa and Zimbabwe. Workshops in these case studies will be used to create awareness about the tool and obtain valuable feedback for improving iWEF.

5.2 Deployment, Hosting (website) and Testing of the web-based iWEF Tool

After considering relevant factors, such as cost, further provided services and security, a domain was procured from GoDaddy[26] with the "app" extension. Thus, the domain name for the iWEF model eventually became https://iwef.app, whose home page is shown in Figure 28. To enhance the user experience and efficiency of the iWEF model, bucket storage services were procured from Amazon Simple Storage Service (Amazon S3)[27] by Amazon Web Services, Inc. iWEF was deployed online on 19th February 2022. The iWEF model website is dynamic, and its content will be regularly updated according to feedback from users and partners. Currently, the developers are in charge of administrating the iWEF model website, including maintenance and updating the iWEF model site and handling user feedback and inquiries.

[26] https://www.godaddy.com/
[27] https://docs.aws.amazon.com/AmazonS3/latest/userguide/Welcome.html

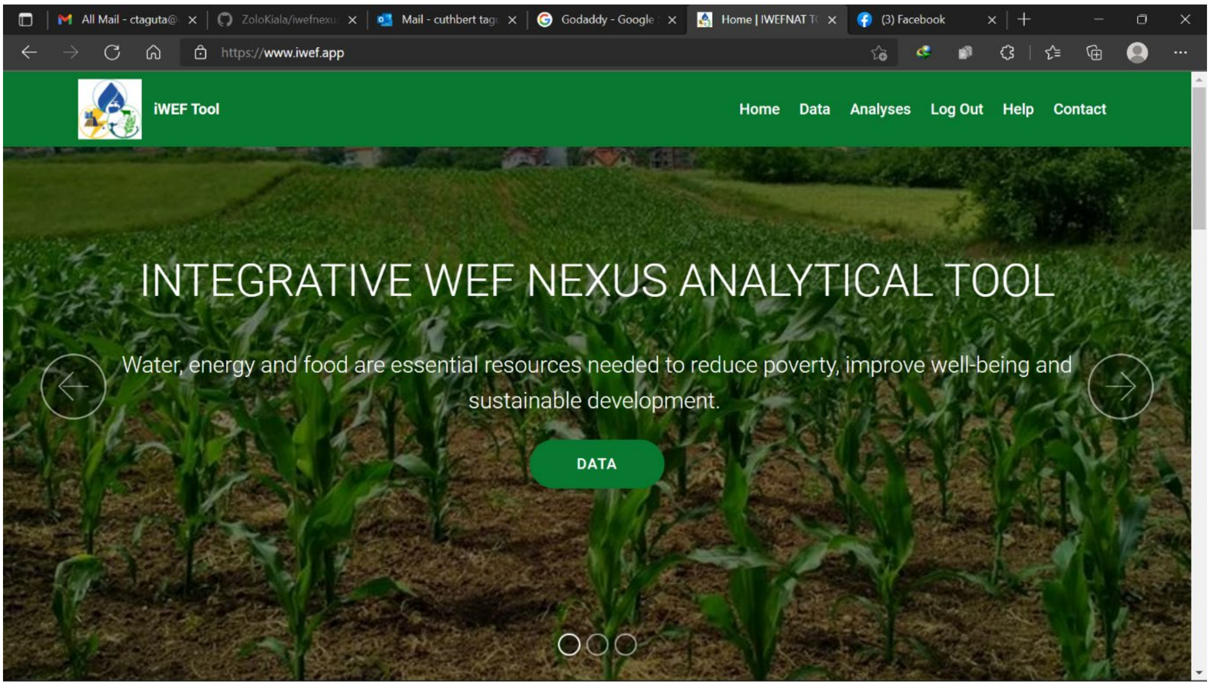

Figure 28: Appearance of home page for iWEF model

A Quick Response (QR) code (Figure 29) for the iWEF model's website was created using QRCode Monkey[28]. Users can scan the QR code using their electronic devices, and they will be redirected and connected to the iWEF model website page right away. This code can be shared online through social media, websites and email; or printed through promotional such as factsheets.

[28] https://www.qrcode-monkey.com/

Figure 29: Website QR code for iWEF model

5.3 Manual Guidelines and Video Tutorials

This section presents the material prepared to familiarize users with the iWEF model.

5.3.1 iWEF user manual

The detailed user manual for iWEF was prepared and uploaded onto the “Help” page of the iWEF app. It is simple, easy to follow and readily available for download by interested users. The part appearance of the first page for the iWEF user manual is shown in Figure 30, while the whole manual is attached in Appendix 2.

iWEF 1.0: A WEB-BASED AND GIS-ENABLED INTEGRATIVE WATER-ENERGY-FOOD (WEF) NEXUS ANALYTICAL MODEL

User Manual

Cuthbert Taguta[1, 2], Zolo Kiala[2, 3], Tsitsi Bangira[2], Luxon Nhamo[4], Aidan Senzanje[1], Tafadzwanashe Mabhaudhi[2, 5]

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[5]*International Water Management Institute (IWMI-GH), West Africa Office, c/o CSIR, Accra, Ghana; and KNUST, Kumasi, Ghana*

Background of iWEF

iWEF was originally developed by Nhamo et al. (2020a) as an MS Excel-based model for establishing quantitative relationships among WEF nexus sectors to indicate resource utilisation and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention. It was recently further developed into an open-source web-based GIS-enabled integrative WEF nexus analytical model with geospatial analytic abilities. To facilitate WEF nexus performance assessment, monitoring and evaluation, iWEF holistically evaluates synergies and trade-offs to improve efficiency and productivity in resource use and management for sustainable development.

Figure 30: Part appearance of first page for iWEF user manual

Sample (prototype) consistent and inconsistent data used in testing and validating the CR calculation functions in the iWEF model is attached in the user manual. This is meant to assist users in familiarizing themselves with the CR concept in the iWEF model.

5.3.2 iWEF video tutorial

A detailed video tutorial was prepared, and this can be accessed on the iWEF tool home page by interested users. The video tutorial explains the necessary steps in using the iWEF model. The video was also uploaded on the dedicated iWEF YouTube channel, while its link was posted and shared on all iWEF media pages, including Facebook, Twitter, Instagram and LinkedIn.

5.4 Maintenance and Monitoring of the iWEF Tool

Meanwhile, the developing team will do maintenance and upkeep of the iWEF model and will also respond to issues raised by users. The team will also continuously update the tool as and when necessary.

5.5 Visual Identity, Promotional and Communication Materials)

The provisional logo (Figure 31) for the iWEF model will be part of all media related to the model. The model's logo promotes instant public recognition and defines the visual and graphical identity of the project as a whole. It consists of three overlapping circles representing the three WEF sectors. The water sector is symbolised by a blue upper circle enclosing a water drop (blue) and a water tap (white). The energy sector is represented by a yellow left circle enclosing the Sun (yellow-orange), solar photovoltaic panels (blue with whitish grids), a dam (blue) and a lightning spark (yellow-orange). The food sector is represented by a green right circle enclosing an irrigating sprinkler (blue), crop (green), and a domestic animal (green).

Figure 31: Provisional logo for iWEF model

5.6 Media and Social Channels

In addition to the official iWEF application website, communication and social media channels have been set up on LinkedIn, YouTube, Facebook, Twitter, Instagram and SlideShare. This section presents the iWEF model's communication channels, including social, media and professional. These channels aim to facilitate the communication of the iWEF-related activities to a wide external audience and promote the visibility of the modelling tool on the most popular channels.

5.6.1 Administration Email

The official administrator email address for the iWEF model is iwefmodel@gmail.com. This email address is linked to the iWEF model and will be used to receive and address queries from users. The email address is included in all dissemination materials and channels.

5.6.2 LinkedIn

The official LinkedIn account for the iWEF model is named iWEF Model and is linked to the model's email address. The LinkedIn account profile address is https://linkedin.com/in/iwef-model-5a9908233 (Figure 32), with a typical landing page as shown in Figure 33. This account is used to disseminate the iWEF model and any updates and news related to the model. The LinkedIn account is valuable for reaching out to the LinkedIn community of professionally oriented audiences.

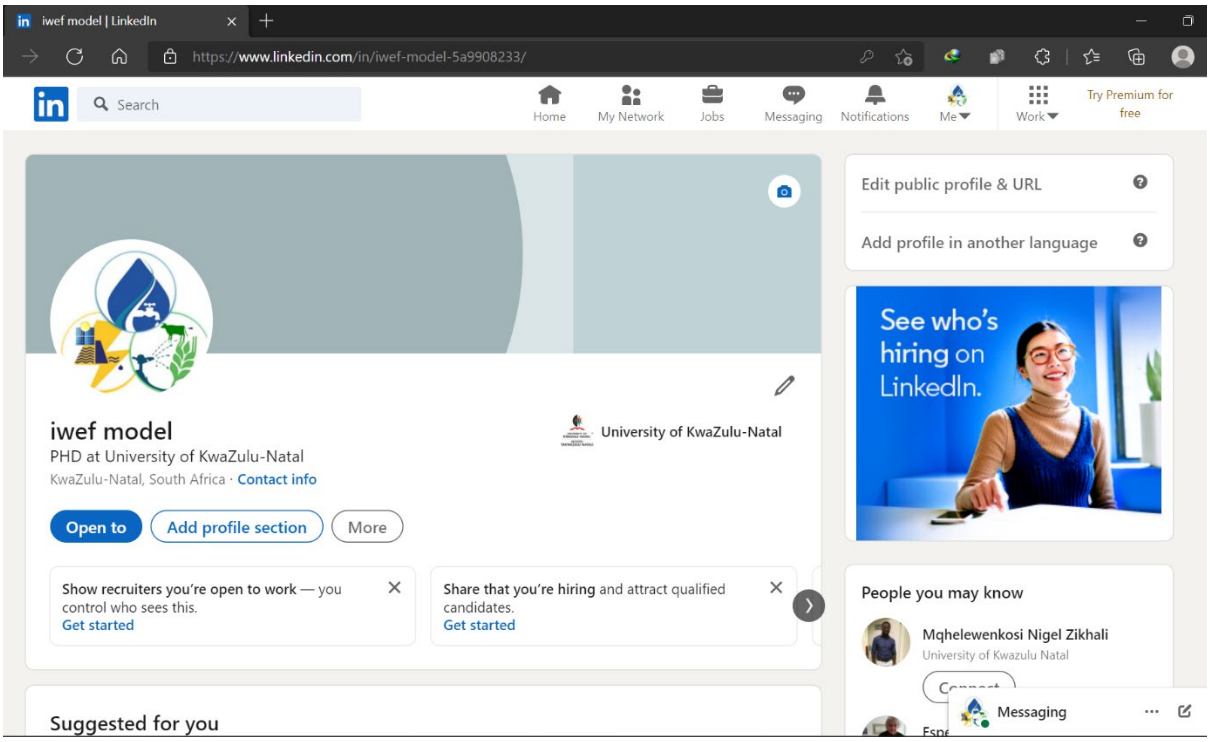

Figure 32: LinkedIn account profile page for the iWEF model

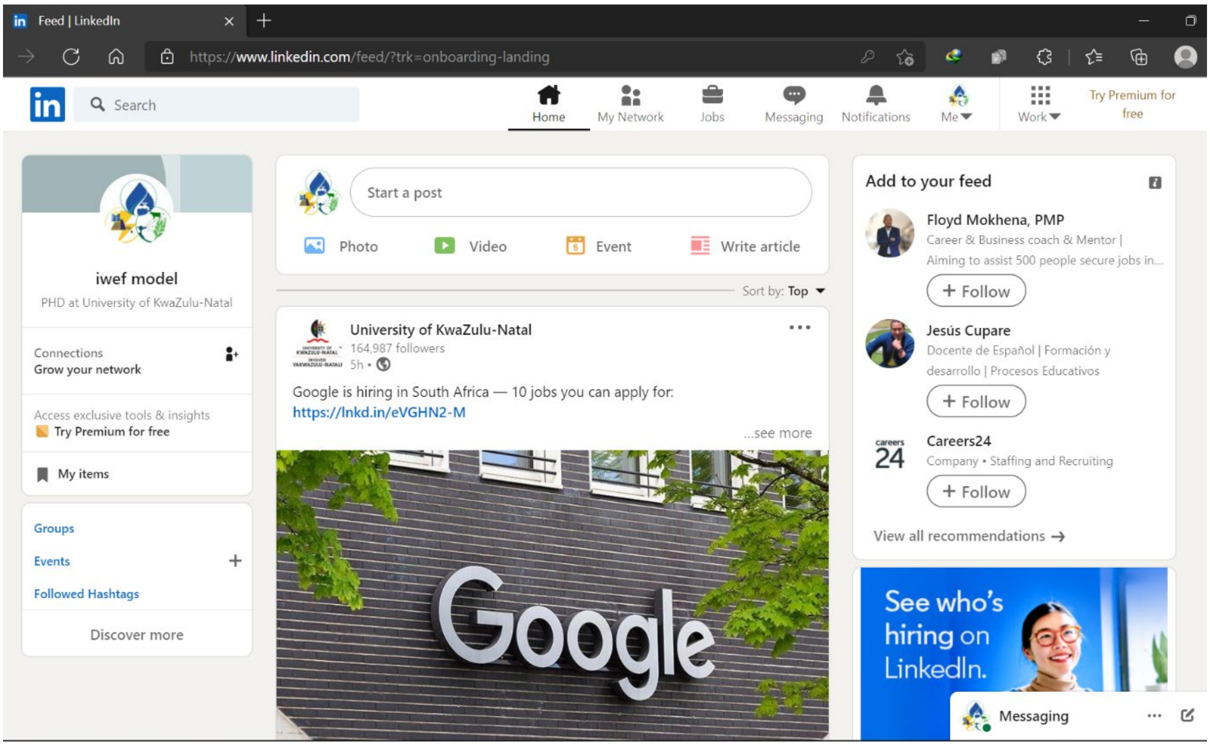

Figure 33: LinkedIn landing page for iWEF model

5.6.3 YouTube Channel

The official YouTube channel is named "iWEF Water-Energy-Food Nexus Modeling Tool", whose link is https://www.youtube.com/channel/UCA_e8Tblx-OdluvHvmzUPxg (Figure 34). It hosts all audio-visual communication and media related to iWEF, including video tutorials for guiding users. The channel is also useful for reaching the YouTube community of users.

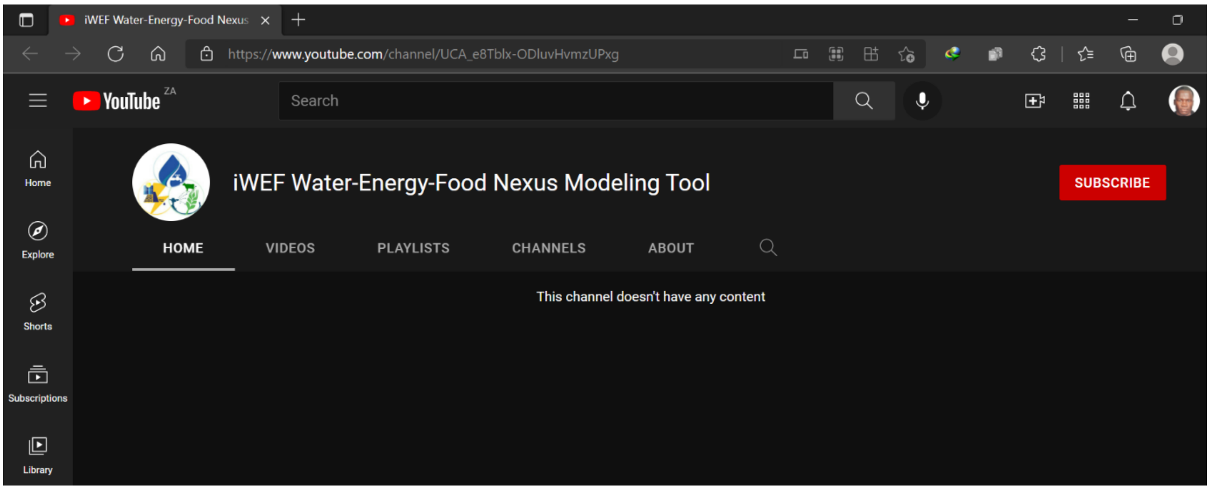

Figure 34: YouTube channel page for the iWEF model

5.6.4 Facebook

The Facebook account name for the iWEF model is *"IWEF Water-Energy-Food Nexus Modeling Tool"*. This account is used to disseminate the iWEF model to the wider Facebook community, and its link is https://web.facebook.com/IWEF-Water-Energy-Food-Nexus-Modeling-Tool-106779441917009 (Figure 35). The Facebook account is also used to share updates, events and news related to the iWEF model.

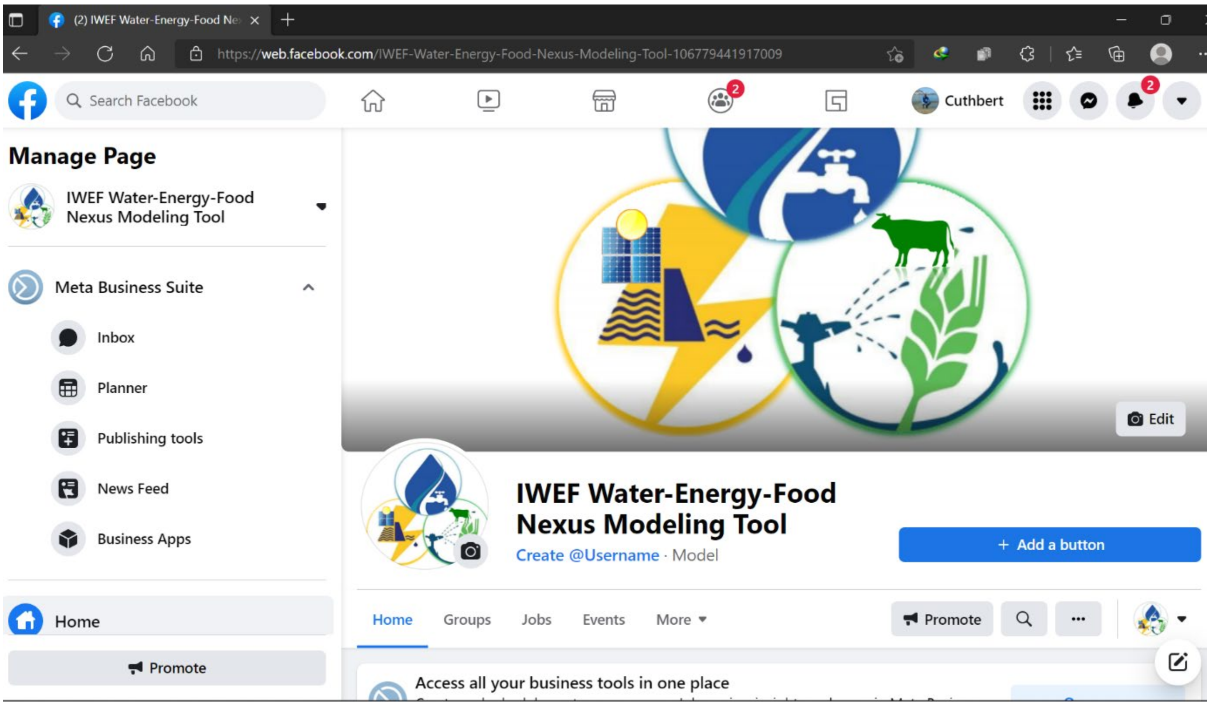

Figure 35: Facebook page for the iWEF model

5.6.5 Twitter

The Twitter username for the iWEF model is "iWEF Water-Energy-Food Nexus Modeling Tool", whose address is https://twitter.com/IwefT (Figure 36). This account will be used as a primary feed to disseminate and promote the iWEF model and post relevant news, updates, and events.

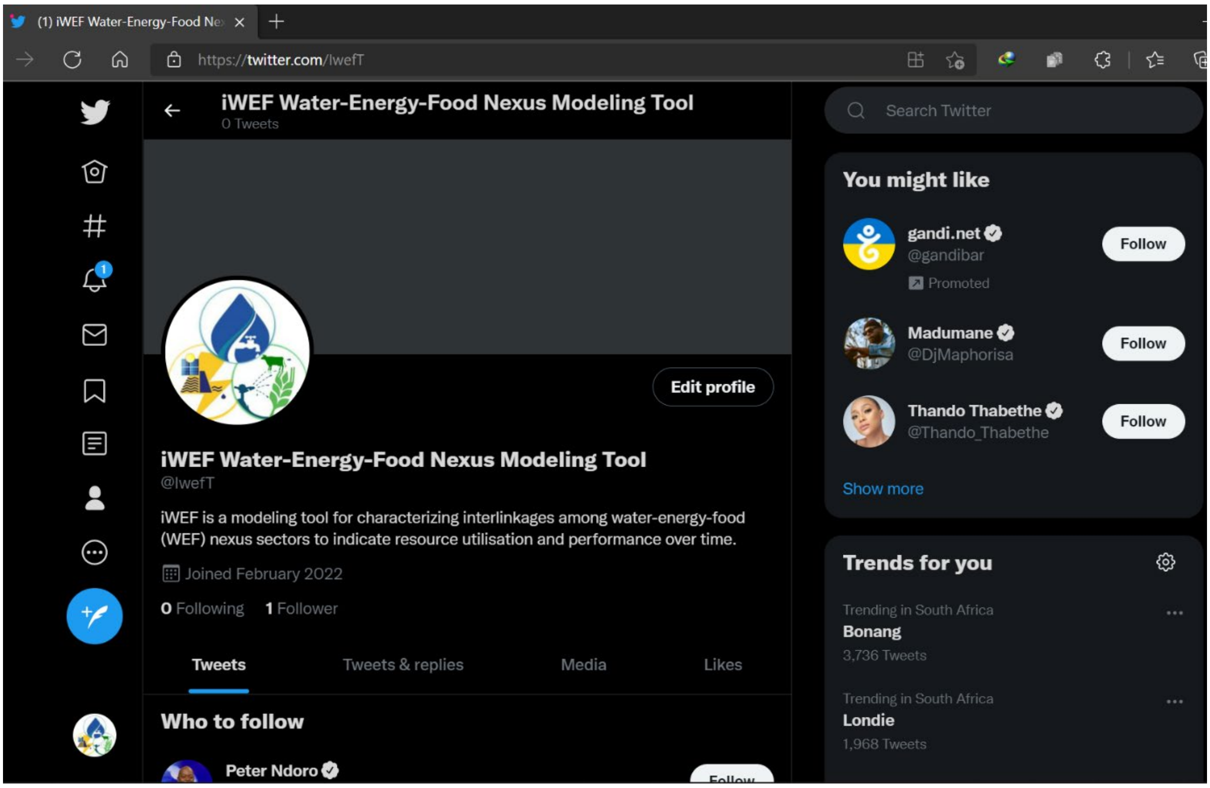

Figure 36: Twitter page for iWEF model

5.6.6 Instagram

The Instagram account for the iWEF model is iwefmodel, whose link is https://www.instagram.com/iwefmodel/ (Figure 37). This account will be used to disseminate and promote the iWEF model to the Instagram community and update them on events and news.

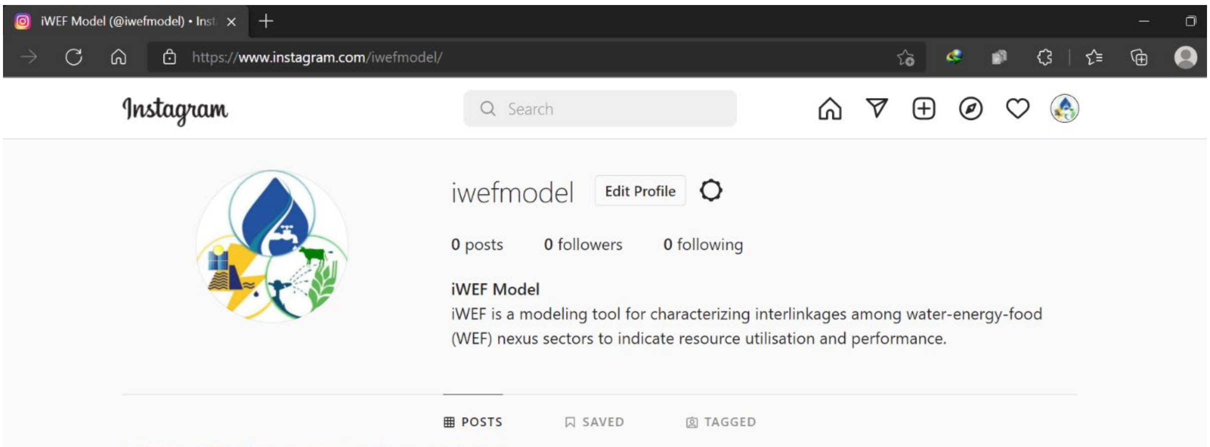

Figure 37: Instagram page for iWEF

5.6.7 SlideShare

The official SlideShare account name is iWEF Model, whose link is https://www.slideshare.net/iWEFModel. This account will be used to disseminate and promote the iWEF model and presentations to the SlideShare community and update them on events and news. The SlideShare account is linked to the LinkedIn account.

5.7 Press Releases

To promote wide uptake and disseminate the iWEF model, press releases are planned for news outlets and newsletters with a wider relevant audience, including WRC's Water Wheel[29] and UKZN's NdabaOnline[30]. The planned releases will be distributed through project communication channels and the channels of the individual partner organizations.

5.8 Partners' Channels

The partners' channels include the University of KwaZulu-Natal Centre for Transformative Agriculture and Food Systems (UKZN-CTAFS; https://ctafs.ukzn.ac.za/) and the Water Research Commission (WRC; http://www.wrc.org.za/). UKZN-CTAFS hosted the researchers and one postgraduate student who conducted this research work, while WRC funded the project. Partner logos on the iWEF website link to the respective partner websites.

5.9 Networking Activities (training/schools, conferences, workshops, collaboration, and liaisons)

Targeted events include high school training, WEF nexus summer and winter schools, and events such as conferences, workshops and symposiums. Future workshops by the WRC funded project C2019/2020-00007 (FROM THEORY TO PRACTICE: DEVELOPING A CASE STUDY AND GUIDELINES FOR WATER-ENERGY-FOOD (WEF) NEXUS IMPLEMENTATION IN SOUTHERN AFRICA) project in case study areas in which iWEF will be applied will act as dissemination events and activities for the model. Other target events include those by International Commission on Irrigation and Drainage (ICID), SADC WaterNet, American Geophysical Union (AGU) and European Geosciences Union (EGU).

5.10 Scientific Publications

Scientific work based on project methodologies, processes and results is being published by the iWEF model developers in open access publications.

The first manuscript, ***"Water-energy-food (WEF) nexus tools in theory and practice: a systematic review",*** was approved for production and accepted in Frontiers of Water, section

[29] http://www.wrc.org.za/the-water-wheel/
[30] https://ndabaonline.ukzn.ac.za/UkzndabaNewsletter/Vol10-Issue4

Water and Human Systems. In this manuscript, the PRISMA protocol was used to systematically review the literature on trends in developing existing WEF nexus tools, their availability in the public webspace, their format, geographical scales of application, and geospatial analytic capabilities, and their application in case studies. On trends in developing WEF nexus tools, the manuscript traces the emergence of tools dedicated to the WEF nexus with time. Regarding their availability in the public webspace, the manuscript searches for the existing WEF nexus tools on the internet to test if they are readily accessible and reachable to interested users. In terms of geographical application scales, the manuscript categorizes the existing WEF nexus tools according to their geographic scopes as presented by developers and in case studies. As for geospatial analytic capabilities, the manuscript interrogates the presence, nature, potential and importance of integrating existing WEF nexus tools with systems for geospatial analysis and visualization such as GIS. Concerning application in case studies, the manuscript traces the frequency and popularity of using existing WEF nexus tools in practice, such as real case studies and their hypothetical simulations. At least one more publication on iWEF development and testing will be drafted and submitted to DoHET accredited journals.

A second manuscript, ***"Introducing iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical model",*** is currently in preparation as the background paper for the iWEF model. It will focus on how the iWEF model was founded, developed, deployed online and tested. The target journal for this publication is Environmental Modelling & Software[31] by Elsevier due to its relevance and high impact factor.

5.11 Conclusion

The dissemination of iWEF for its wide uptake has already started and is an ongoing process that will use various communication channels to reach out to diverse audiences. Local and international events and ongoing WEF nexus projects will also be leveraged. The scientific audience will be engaged through scientific publications and gatherings, some of which are already in press and preparation.

[31] https://www.journals.elsevier.com/environmental-modelling-and-software

CHAPTER 6 POLICY BRIEFS ASSOCIATED WITH THE WEB-BASED GIS-ENABLED WEF NEXUS TOOL

6.1 Introduction

Policy briefs are now part and parcel of regular communications between technocrats and policymakers or strategists. But then, what is a policy brief? The term policy brief describes several documents that serve more or less the same purpose. Some of the common names include; *Technical Note*, *Policy Note*, *Evidence Brief*, *Evidence Summaries*, *Research Snapshot*, and the like. The definitions ascribed to policy briefs can vary just as much and could be placed on a continuum going from the most "neutral" to the most "interventionist". Still, both definitions are always founded on scientific evidence. The "neutral" policy brief provides nuanced information to give an overall picture of the situation of a given problem (Douglas and Ridde, 2017), whereas the most "interventionist" policy brief puts forward solutions to a problem and seeks a quick change. In line with the above, some argue that there are (only) two basic types of policy briefs – an "advocacy" brief that argues in favour of a particular course of action or an "objective" brief that gives balanced information for the policymaker to make up their own mind (FAO, nd).

In short, a policy brief is a concise summary of a particular issue, the policy options to deal with it, and some recommendations on the best option (FAO, nd). It is aimed at government policymakers and others interested in formulating or influencing policy. A policy brief is a key tool to present research and recommendations to a non-specialized audience. Policy briefs serve as a vehicle for providing evidence-based policy advice to help readers make informed decisions. A strong policy brief distils research findings in plain language and draws clear links to policy initiatives. The best policy briefs are clear and concise stand-alone documents that focus on a single topic.

As the name suggests, policy briefs are targeted at policymakers. It is a known fact that policymakers are busy people and not necessarily specialists in the topic under research by technocrats. They are likely to read only something that looks attractive, appears interesting, and is short and easy to read (FAO, nd). It is therefore imperative that a policy brief should, amongst other things; provide enough background for the reader to understand the problem, convince the reader that the problem must be addressed urgently, provide information about alternatives (in an objective brief), provide evidence to support one alternative (in an advocacy brief), and stimulate the reader to make a decision (FAO, nd). To achieve its objectives, a policy brief should; be short and to the point, be based on firm evidence, focus on meanings, not methods, and relate to the big picture of the subject.

There are many ways of structuring a policy brief, but whatever the format, the issues, expectations and requirements discussed above must be satisfied by the resultant policy brief. Typically, a policy brief is structured to have; a clear *Title*, an informative *Executive*

Summary, a convincing *Context or Scope of the Problem*, an accurate presentation of *Policy Alternatives*, and clear *Policy Recommendations* and *Conclusions*. In terms of document length, a policy brief should be a 1-pager to remain short and easy to read by the policymaker.

In the context of the current project, as part of the expectations and fulfilling Specific Objective 5 on "*To compile a generalised policy brief in association with stakeholders and the National Planning Commission (NPC) that will support the transition of energy from mainly fossil fuels to renewables throughout South Africa based on the evidence for the WEF nexus model*", one policy brief has been drafted as indicated below. This forms the first part of engaging with stakeholders to develop final policy briefs that answer the above-stated objective. Stakeholder interactions are ongoing and will continue outside the ambit of the current short-term project that ends on the 31st March 2022. The drafted policy brief is targeted at policymakers.

6.2 Policy Briefs – Policy Makers

TITLE

From Theory to Practice – Embedding the iWEF Nexus as a Natural Resources Management Tool in Everyday Operations at the National Planning Commission Level

EXECUTIVE SUMMARY

The iWEF nexus tool is a user-friendly web-based GIS-enable tool for managing natural resources (WEF nexus resources) at multiple scales. The tool needs to be embedded as a planning tool in the day-to-day operations of the National Planning Commission (NPC). Natural resources planning is coordinated at the national scale to bring together water, energy, and agriculture sectors.

CONTEXT

Strategic resources such as water, energy, food, and land are under pressure from changes in climate and socioeconomic conditions and silo-based management approaches. This has led to the pursuit of integrated resource management approaches: the water-energy-food (WEF) nexus. The water-energy-food (WEF) nexus approach acknowledges the inextricable links between WEF resources to maximize and minimize their synergies and trade-offs. The complex linkages between these resources require user-friendly and readily available models and tools to analyse the systems. The tools must be robust, accurate, reliable, and use modern platforms like the web-enabled and GIS-based for data handling.

OBJECTIVE

The iWEF nexus tool was developed to meet the requirements of a reliable, accurate and robust tool that enables the analysis of water, energy, and food resources at multiple scales using a web-based platform and having GIS capabilities.

OUTCOMES

The iWEF nexus tool is web-based, GIS-enabled, and applicable at multiple scales. It gives accurate, reliable results in WEF nexus analysis.

RECOMMENDATION and POLICY ISSUE

It is recommended that the iWEF nexus tool be embedded as a planning tool in the day-to-day operations of the National Planning Commission (NPC), where natural resources planning is coordinated at the national scale to bring together water, and energy and agriculture sectors.

6.3 Conclusion

Policy briefs are an essential part of everyday communications between technocrats and policymakers. The purpose, format, structure, compilation and presentation of generic policy briefs are well known and discussed in this chapter. As the name suggests, policy briefs are by nature short and to the point, interesting to read, and adequately informative, whether they are advocacy or objective policy briefs.

In the context of the current research project, one draft policy brief is presented focusing on moving from theory to practice concerning the WEF nexus as a planning tool in South Africa, and with a specific focus on the applicability of the developed iWEF Nexus tool. This is for policymakers, although other policy briefs are required for natural resources planners and other interested parties who may use the iWEF Nexus tool in research or localised management of natural resources.

CHAPTER 7 SUMMARY, CONCLUSION, KEY RECOMMENDATIONS

7.1 Summary

Strategic resources such as water, energy, food, and land are under pressure from changes in climate and socioeconomic conditions and silo-based management approaches. This has led to the pursuit of integrated resource management approaches: the water-energy-food (WEF) nexus. The water-energy-food (WEF) nexus approach acknowledges the inextricable links between WEF resources to maximize and minimize their synergies and trade-offs. This short-term project was part of the WRC's goal to promote the WEF nexus research and implementation in South Africa. To bridge the gap between WEF nexus theory and practice, the global aim of this study was to develop a web-based and GIS-enabled integrative WEF nexus analytic model, iWEF. Specifically, the work reviewed state-of-the-art WEF nexus models tools, and developed, tested and disseminated a web-based GIS-enabled WEF nexus analytical tool applicable at different scales.

7.2 Conclusions

With respect to the specific objectives of the study put forward to achieve the global goal stated above, the following conclusions were reached;

A systematic review of WEF nexus applications and tools: The systematic review was successfully conducted and identified 46 WEF nexus tools, of which 39% were available for public use, 43% were hosted on the public web domain, 48% applied to large spatial scales and just under 30% possessed geospatial analytical capabilities.

Develop a web-based GIS-enabled WEF nexus tool: A web-based GIS-enabled WEF nexus tool, herein called the iWEF Nexus tool, was successfully developed from the Integrative WEF Nexus Analytical tool model developed under the auspices of a WRC funded research project. The non-quantitative conceptual model of the iWEF nexus tool was founded on the (AHP) multi-criteria decision making (MCDM) framework, which consists of the goal, indicators and pillars. The goal constitutes the objective to analyse the quantitative and spatial dynamics of the WEF nexus. The six indicators speak to the security of the three WEF pillars (water, energy and food). The quantified conceptual model of the iWEF tool is expressed in mathematical terms and consists of the model's equations, typically including variables whose values are unknown and can vary and parameters whose values are assumed known.

Test the GIS-based tool at various scales for South Africa: Testing the iWEF tool involved running trials to ascertain the model's accuracy and reliability in computing the CR value and the WEF nexus index using data from two existing examples. The model performed satisfactorily. After testing, verification and validation, it can be safely concluded that the web-based GIS-enabled iWEF model is accurate in computing and presenting the WEF nexus at multiple scales.

Facilitate broader dissemination and uptake of the web-based GIS-enabled tool: The iWEF tool has been publicised, and interested stakeholders are invited to try it out or use it. This is an ongoing exercise that will continue under the auspices of the WRC.

Compile a generalised policy brief: Draft policy briefs have been compiled. These will be updated as broader dissemination of the iWEF tool continues beyond the life of the current project.

7.3 Key Recommendations and the Way Forward

The key recommendation from this research include;

- Further enhancements of the geospatial capabilities of the iWEF nexus tool for ease of uploading different forms of data.
- Further dissemination of the iWEF nexus tool to a wider range of stakeholders involved in WEF Nexus research and applications in the South and the region, and even globally.
- Finalise the compilation of impactful policy briefs to go with the iWEF nexus tool

In terms of the way forward, research and application activities involving the iWEF nexus tool must remain active, at least the tool falls "off the radar" and is soon forgotten. The WRC has to take centre stage on this since UKZN's (the researchers) mandate will end with the end of the project on 31st March 2022.

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APPENDICES

Appendix 1: Characteristics of existing 46 WEF nexus tools

Tool	Availability		Format/form of tool							Spatial scale of application					Geospatial capabilities	Number of case studies		
	Av	*W*	*DL*	*WA*	*DA*	*Cod*	*Ex*	*Ge*	*Un*	*G*	*Con, ER, B, Tr*	*Cou, N*	*P, SB, Ca*	*L (Sc, M, H, Ci, To, Proj)*		*L (1-3)*	*M (4-10)*	*H (>10)*
WEF Nexus Discovery Map (1)	✓	✓		✓						✓	✓	✓	✓	✓	✓			✓
BP-DEMATEL-GTCW (2)									✓		✓		✓	✓				✓
ITEEM (3)						✓					✓				✓	✓		
WEF-Sask (4)									✓		✓					✓		
CALFEWS (5)	✓	✓				✓						✓				✓		
NeFEW (6)	✓	✓			✓							✓				✓		✓
MAXUS (7)					✓							✓	✓	✓	✓			✓
WEF Nexus SD (8)									✓				✓			✓		
FPC (9)							✓							✓		✓		
WEF-P (10)									✓		✓					✓		
SD-WFE Model (11)									✓				✓					✓
WEST Tool (12)	✓	✓				✓						✓	✓			✓		
MIFCP-WEFN Model (13)									✓				✓			✓		
NEST Tool (14)	✓	✓				✓					✓				✓	✓		

Appendix 1: Characteristics of existing 46 WEF nexus tools, Continued

Tool	Availability		Format/form of tool								Spatial scale of application				Geospatial capabilities	Number of case studies		
	Av	*W*	*DL*	*WA*	*DA*	*Cod*	*Ex*	*Ge*	*Un*	*G*	*Con, ER, B, Tr*	*Cou, N*	*P, SB, Ca*	*L (Sc, M, H, Ci, To, Proj)*		*L (1-3)*	*M (4-10)*	*H (>10)*
iWEF Tool (15)							✓				✓	✓	✓	✓		✓		
WEF Nexus Index (16)	✓	✓		✓								✓			✓			✓
AWEFSM Model (17)									✓		✓		✓	✓		✓		
GREAT for FEW Tool (18)	✓	✓		✓								✓			✓	✓		
EPAT (19)									✓			✓	✓			✓		
WHAT-IF (20)	✓	✓				✓					✓		✓			✓		
K-WEFS (21)									✓					✓		✓		
WEFSiM (22)									✓			✓				✓		
Daily (23)									✓		✓		✓		✓	✓		
DAFNE (24)			✓						✓		✓				✓	✓		
SIM4NEXUS Model and Serious Game (25)	✓	✓							✓				✓		✓			✓
UCEC (26)	✓	✓		✓										✓		✓		
ABM-SWAT (27)									✓		✓					✓		
Nexus Game (28)	✓							✓			✓							✓
WEF (29)					✓									✓		✓		
Q-Nexus (30)	✓	✓		✓								✓					✓	
NexSym (31)					✓									✓		✓		

Appendix 1: Characteristics of existing 46 WEF nexus tools, Continued

Tool	Availability	Format/form of tool							Spatial scale of application					Geospatial capabilities	Number of case studies		
	Av	*W*	*DL*	*WA*	*DA*	*Cod*	*Ex*	*Ge*	*Un*	*G*	*Con, ER, B, Tr*	*Cou, N*	*P, SB, Ca*	*L (Sc, M, H, Ci, To, Proj)*		*L (1-3)*	*M (4-10)*	*H (>10)*
WEFO (32)									✓		✓					✓		
SEWEM (33)									✓		✓		✓			✓		
BRAHEMO (34)									✓		✓					✓		
IBMR-MY (35)									✓		✓					✓		
Pardee RAND WEF Security Index (36)	✓	✓		✓								✓						✓
WEF Nexus Tool 2.0 (37)	✓	✓		✓								✓					✓	
PRIMA (38)		✓	✓		✓								✓		✓		✓	
EWF Nexus Tool (39)									✓			✓					✓	
WEF Nexus Assessment 1.0 (40)		✓	✓						✓			✓	✓	✓			✓	
Nexus Webs (41)									✓	✓	✓	✓	✓	✓		✓		
CLEWs (42)	✓	✓		✓						✓	✓	✓	✓	✓	✓			✓
WEAP – LEAP (43)	✓	✓			✓					✓	✓	✓	✓	✓	✓			✓
Foreseer (44)		✓	✓		✓					✓	✓	✓			✓			✓
ANEMI (45)	✓	✓				✓				✓	✓	✓						✓
MuSIASEM (46)	✓	✓							✓			✓			✓			✓

Key: Av = availability; W = web availability; DL = dead (broken) link; WA = web application; DA = desktop applications; Cod = code; Ex = Excel worksheet; Ge = game; Un = unknown; G = global; Con, ER, B, Tr = Continental, Economic Region, Basin, Transboundary; Cou, N = Country, National; P, SB, Ca = Province, Sub-basin, Catchment; L (Sc, M, H, Ci, To, Proj) = Local (Sub-catchment, Municipal, City, Town, Household, Project); Ge = Geospatial capabilities / features; L (1-3) = Low case studies; M (4-10) = Medium case studies; H (>10) = High case studies

Appendix 2: iWEF User Manual

iWEF 1.0: A WEB-BASED AND GIS-ENABLED INTEGRATIVE WATER-ENERGY-FOOD (WEF) NEXUS ANALYTICAL MODEL

User Manual

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Background of iWEF

iWEF was originally developed by Nhamo et al. (2020a) as an MS Excel-based model for establishing quantitative relationships among WEF nexus sectors to indicate resource utilisation and performance over time, thereby providing evidence of WEF nexus to decision-makers and indicating priority areas for intervention. It was recently further developed into an open-source web-based GIS-enabled integrative WEF nexus analytical model with geospatial analytic abilities. To facilitate WEF nexus performance assessment, monitoring and evaluation, iWEF holistically evaluates synergies and trade-offs to improve efficiency and productivity in resource use and management for sustainable development.

After identifying and defining relevant WEF sustainability indicators, Nhamo et al. (2020a) developed a methodology to compute composite indices. The key input data for iWEF modelling are the six WEF sustainability indicators, per annum, including water availability (m^3/capita), water productivity ($/$m^3$), energy accessibility (%), energy productivity (MJ/GDP), food self-sufficiency (%) and cereal productivity (kg/ha). These indicators are compared pairwise in a pairwise comparison matrix (PCM) based on expert opinion/advice, literature, or recognized databases (e.g. national statistics, World Bank, Aquastat, etc) that can provide the baseline to establish the numerical relationship among indicators (Mabhaudhi et al., 2019; Nhamo et al., 2020a,b). Water availability is the proportion of available freshwater resources per capita, which estimates the total available freshwater water resources per person. Water productivity is the proportion of crops produced per unit of water used, which measures the output from an agricultural system in relation to the water it consumes. Energy accessibility is the proportion of the population with access to electricity, expressed as a percentage (%) of the total population. Energy productivity is synonymous with energy intensity, which is the energy supplied to the economy per unit value of economic output. Food self-sufficiency is the percentage (%) of individuals in the population, out of total population, who have experienced food insecurity at moderate or severe levels during the reference year. Cereal productivity is considered the proportion of sustainable agricultural production per unit area (Nhamo et al., 2020a).

The iWEF tool integrates the six WEF indicators through the Analytic Hierarchy Process (AHP) multi-criteria decision-making (MCDM) approach (Brunelli, 2015) by normalising WEF indicators data to determine composite indices used to compute the weighted average WEF nexus index. According to Saaty (1987), the AHP is a theory of measurement for deriving ratio scales from both discrete and continuous paired comparisons to set priorities and make the best decisions. The AHP comparison matrix is determined by comparing two indicators at a time using Saaty's scale, which ranges between 1/9 and nine as indicated in the Table 1 (Saaty, 1987). To create the PCM for your case study, be guided by Table 1 wherein *a* and *b* are the row and column factors/indicators, respectively.

Table 1: Saaty's scale of relative importance for pairwise comparisons in an AHP

Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Element *a* and *b* contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour element *a* over *b*
5	Essential or strong importance	Experience and judgment strongly favour element *a* over *b*
7	Very strong or demonstrated importance	Element *a* is favoured very strongly over *b*; its dominance is demonstrated in practice
9	Extreme or absolute importance	The evidence favouring element *a* over *b* is of the highest possible order of affirmation
2 (weak), 4 (moderate plus), 6 (strong plus), 8 (very, very strong), 1/2, 1/4, 1/6, 1/8	Intermediate values between the two adjacent judgments	When compromise is needed. For example, 2 can be used for the intermediate value between 1 and 3
1/3	Moderately less important	
1/5	Strongly less important	
1/7	Very strongly less important	
1/9	Extremely less important	
Reciprocals of above nonzero	If *a* has one of the above nonzero numbers assigned to it when compared with *b*, then *b* has the reciprocal value when compared with *a*	A reasonable assumption

Source: Saaty and Vargas (2012)

The iWEF model determines the integrated WEF nexus value which ranges from zero to one and can be interpreted on its level or class of sustainability (Table 2) (Nhamo et al., 2020a). Key outputs in iWEF include a spider graph (radar chart or sustainability polygon) of normalised indices and maps. The shape of the radar chart illustrates WEF nexus indicator performance and inter-relationships, providing a synopsis of the level of interactions, interdependencies and inter-connectedness among WEF nexus sectors, whose management is perceived as either sustainable or unsustainable. The maps show spatial distribution of the WEF nexus in the locations of interest, thus highlighting the hotspots and champions.

Using iWEF

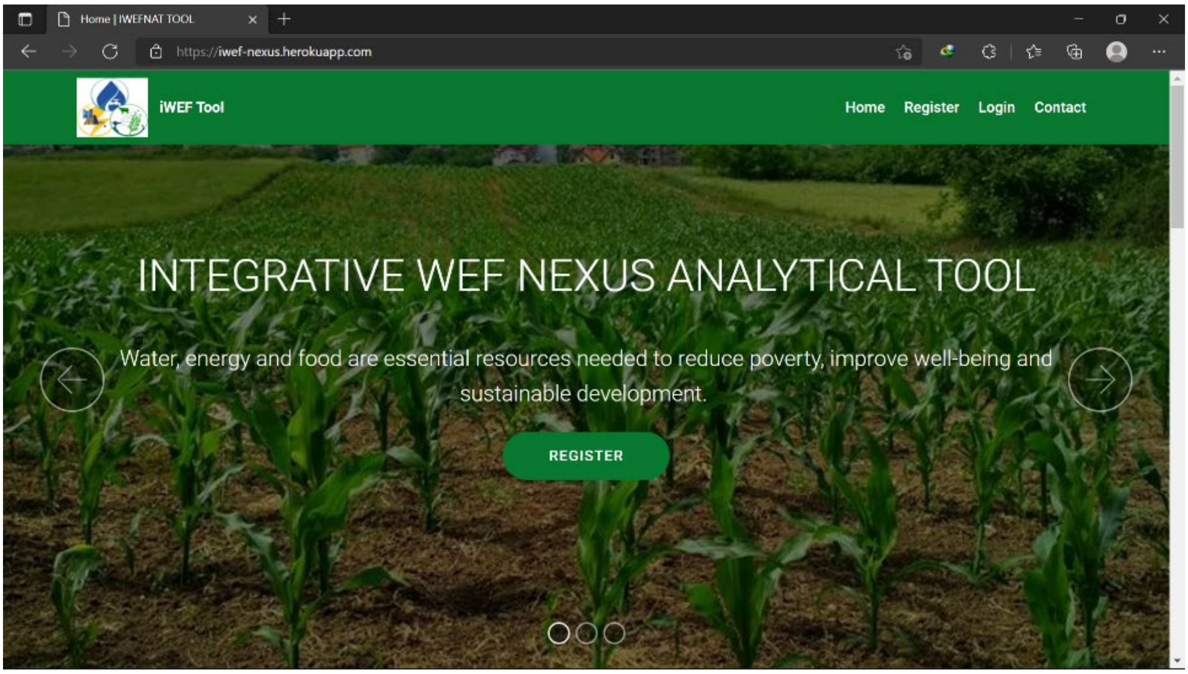
The user interface and corresponding stepwise operating procedures for iWEF are shown in the in the succeeding section. Six steps are designed to carry out a WEF nexus study in the tool.

User interface and corresponding operating procedures of iWEF

<table>
<tr><th>Operating procedures and user interface</th></tr>
<tr><td>

Step 0: Home page

- Visit iWEF tool's landing home page (https://iwef.app/) where you can access the different modules of the tool.

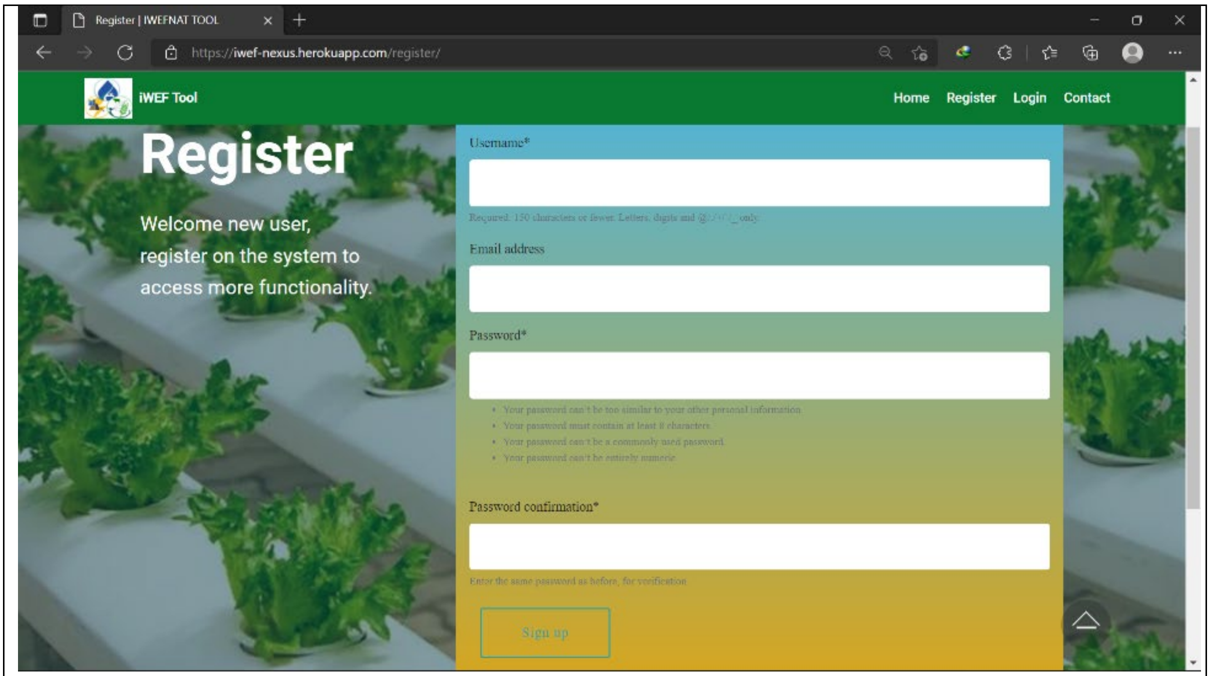


</td></tr>
<tr><td>

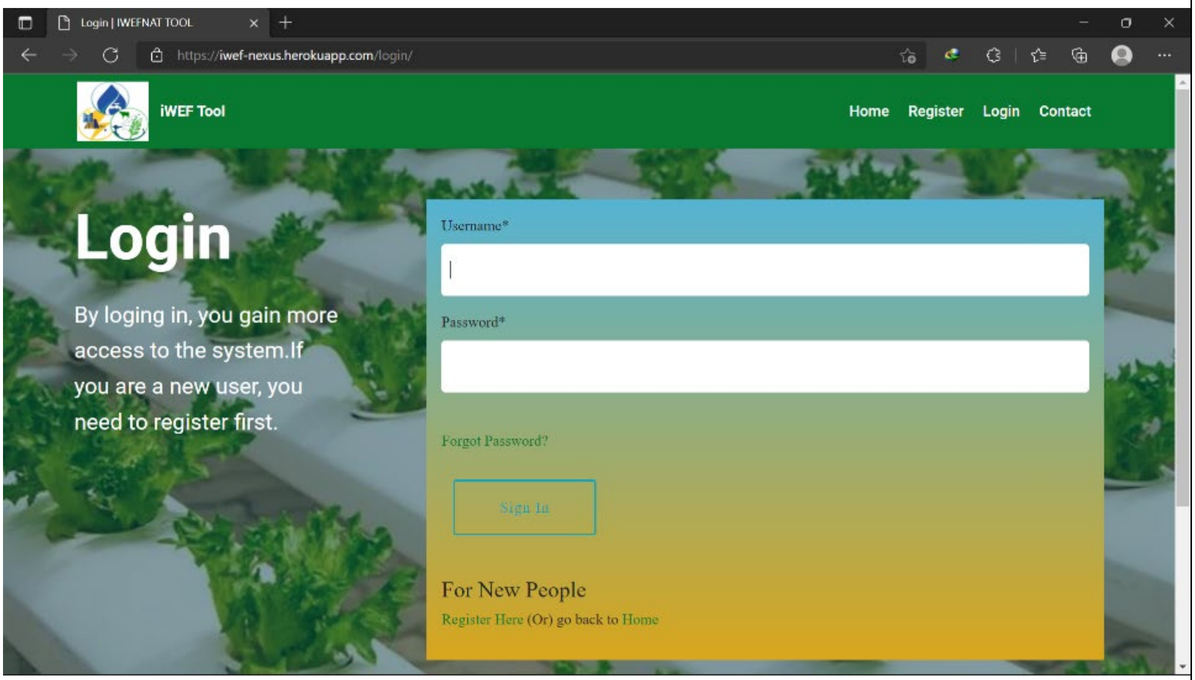
Step 1: User registration and login

- If you are a new user, click the **'Register'** tab and populate the pop-up form with a unique username, email address and password. Click the **'Sign up'** tab and your personal account will be created.

</td></tr>
</table>

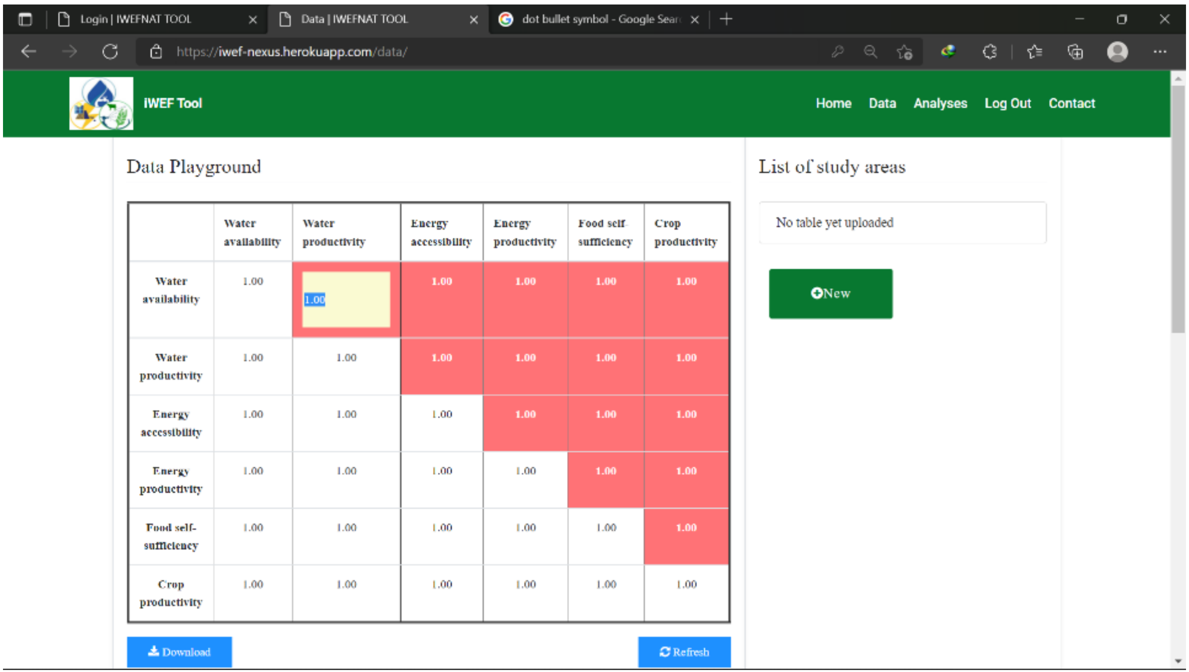


- Click the **'Login'** tab and populate the pop-up form with your username and password, then click the **'Sign In'** tab to access and use the iWEF tool.
- In case you forget your password, click the **'Forgot Password'** tab, and a password renewal link will be sent to your personal email, in the **'Inbox'** or **'Spam'** folder.



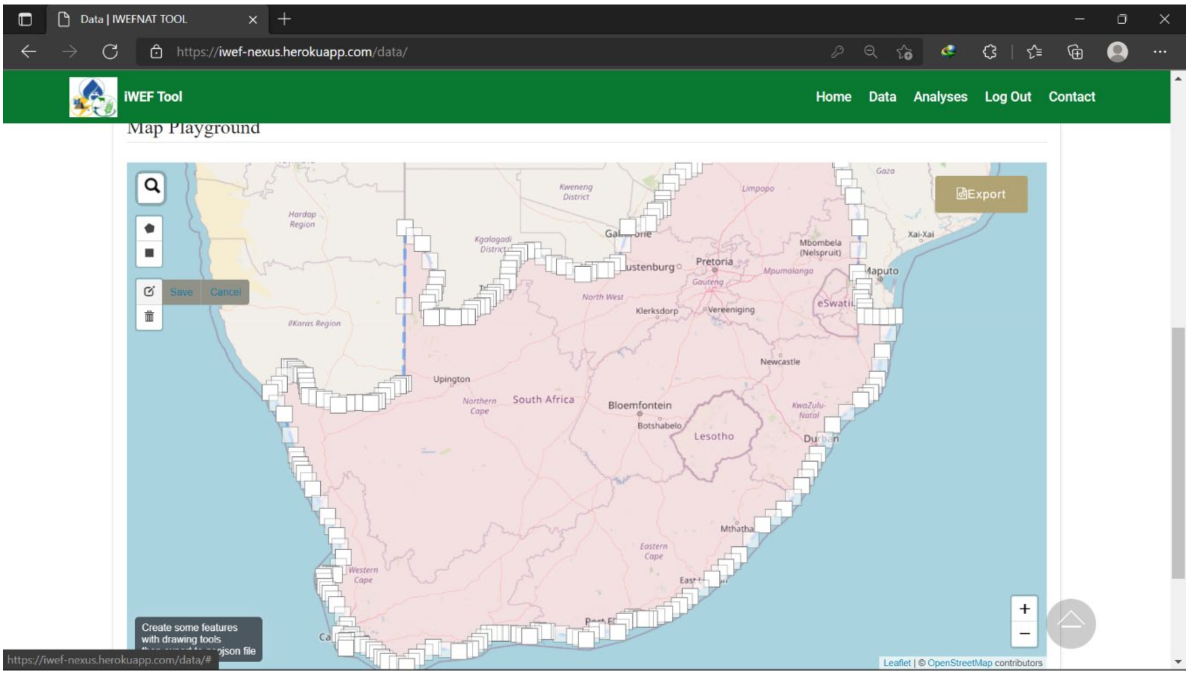
Step 2: Preparing input data

- Click the **'Data'** tab and be guided by Table 1 in filling your input data into all the editable coloured cells above the main / leading diagonal in the indicators data table to replace the default values. The reciprocal cells below the diagonal will be automatically filled for you. For accuracy, it is recommended to fill in fractions instead of decimals for numbers, for example 1/3 for 0.33; 1/6 for 0.17; 1/7 for 0.14; and 1/9 instead of 0.11.
- Click **"Download"** tab to save your data in your local computer (by default, as *'exported-table (1)'* in **Downloads'** folder). Depending on the consistency and randomness of the pairwise comparison judgements, the user will either (i) be able to download their data for analysis if consistency ratio (CR) value is less than 0.10, or (i) be unable to download their data and be prompted to re-evaluate their judgements if CR value is greater than or equal to 0.10. In case of outcome (i) above, the process will be repeated until they get an acceptable CR value (≤ 0.1 or 10%) and download their data for analysis. Renaming the downloaded .csv file is optional.



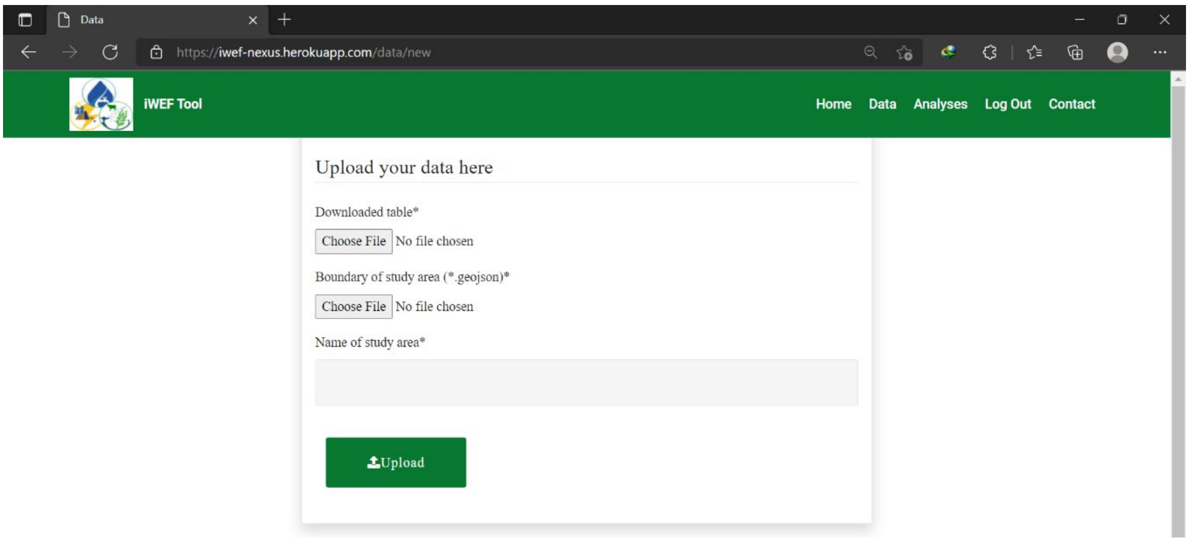
Step 3: Delineating the case study area

- If the user has a conventional .shp shapefile for the case study area, they must create a .geojson shapefile by using (i) the web-based tool http://geojson.io/, or (ii) the QGIS software.
- If the user lacks a conventional .shp shapefile for the case study area, go down to the *'Map Playground'*, select your polygon shape (regular or rectangle), then use the mouse cursor arrow to delineate the boundaries of your case study area in the base map. Zoom in the base map to fine tune the boundaries. Click on the **'Export'** tab to download the shapefile of your selected case study area in your local computer (by default, as *'export_draw_day_month_year'* in **Downloads'** folder). Renaming the saved .geojson file is optional.

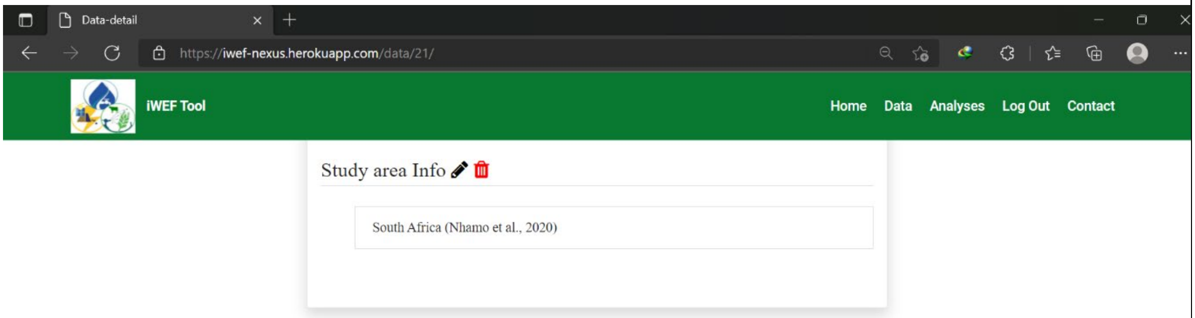


Step 4: Uploading and editing input data

- In the *'List of study areas'* area, click on the **'+New'** tab to open the **'Upload your data here'** area where you will upload your recently saved .csv and .geojson files into the *'Downloaded table'* and *'Boundary of study area'* fields, respectively.
- Specify the preferred name for your case study area in the *'Name of study area'* field. Click the **'Upload'** tab.

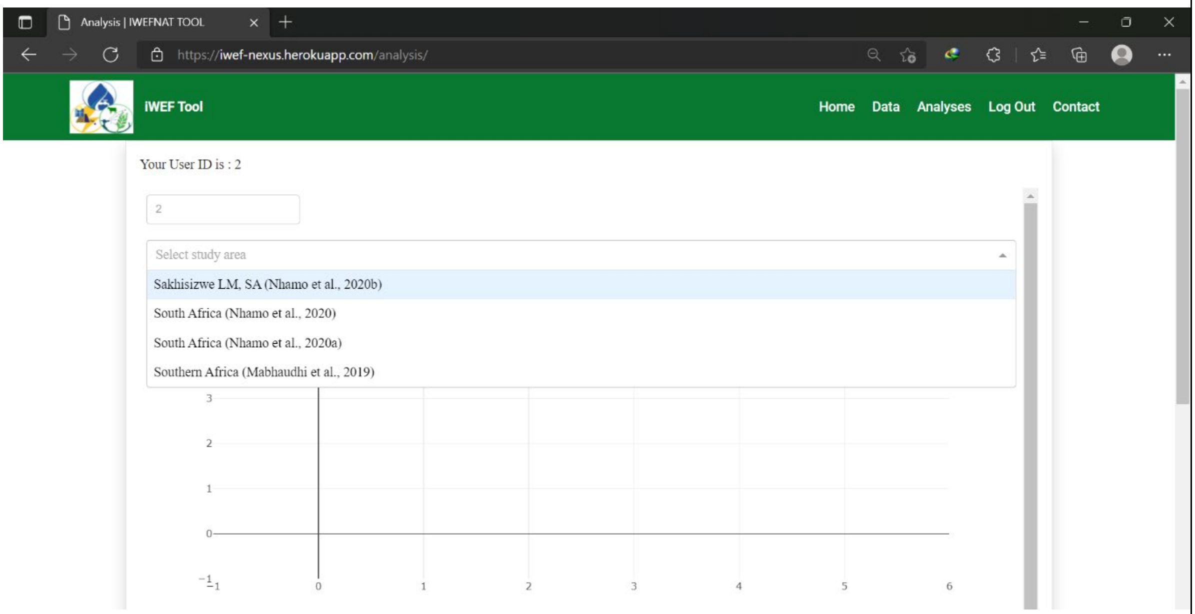


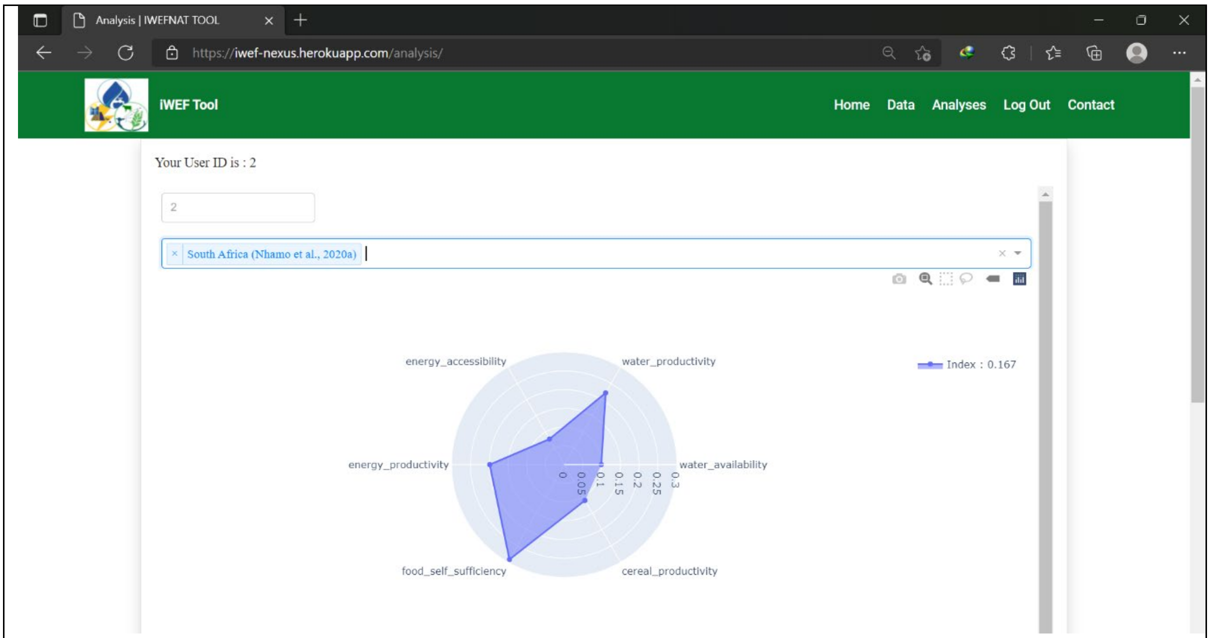
- To edit your uploaded data, click the specific case study and go to the **'Study area Info'** area where you can either **edit** or **delete** your data and case study shapefile.



Step 5: Computing and displaying the WEF nexus index

- Click the **'Analyses'** tab and enter your system randomly generated and assigned ID which is displayed near the top part of page. Click in the '*Select study area'* field and your uniquely identified case studies will appear in a draw-down list. Select the case study of interest and your results will be displayed as a radar chart (or spider diagram) and a colour coded map. Download these results as .png for exporting and reporting.

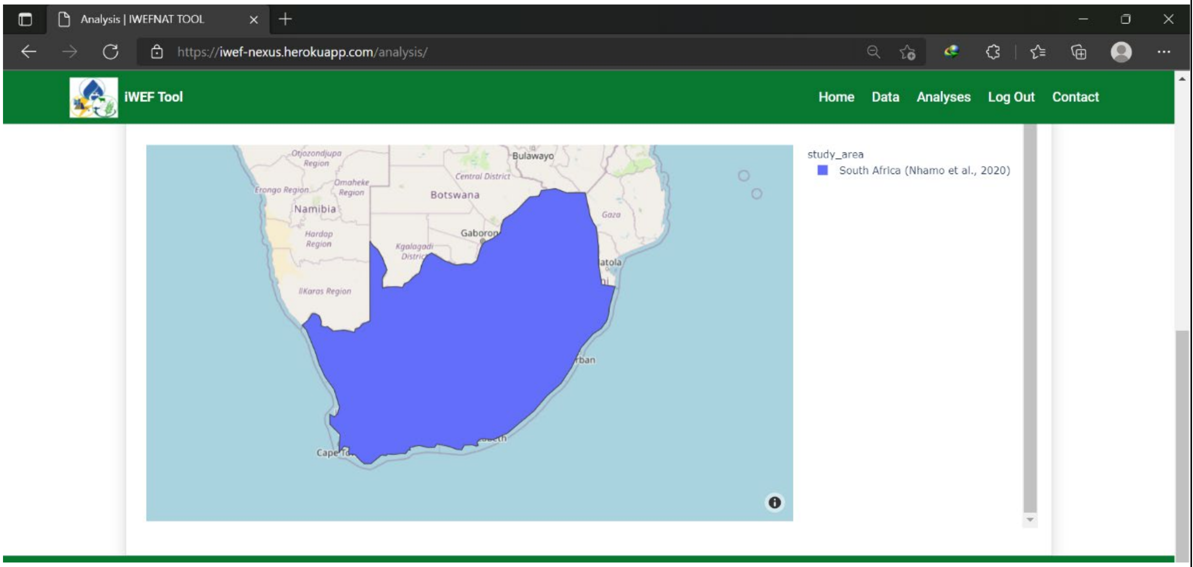




- The value(s) of the individual indices and integrated WEF nexus index can be interpreted according to Table 2.

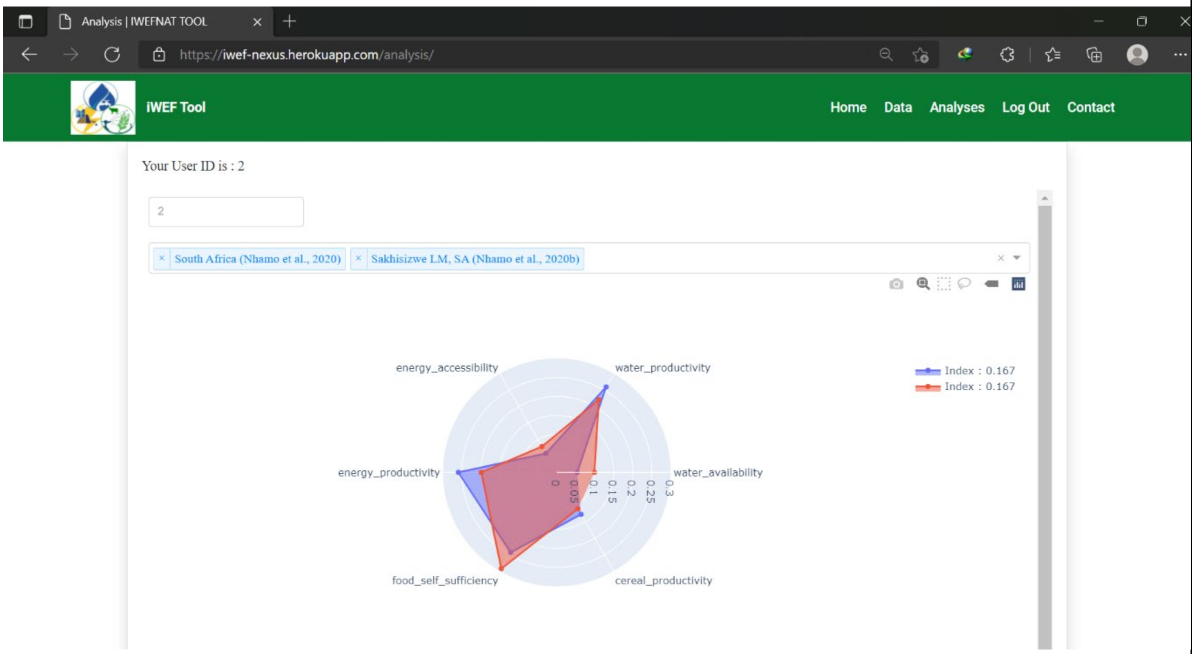
Table 2: WEF nexus indicators performance classification categories

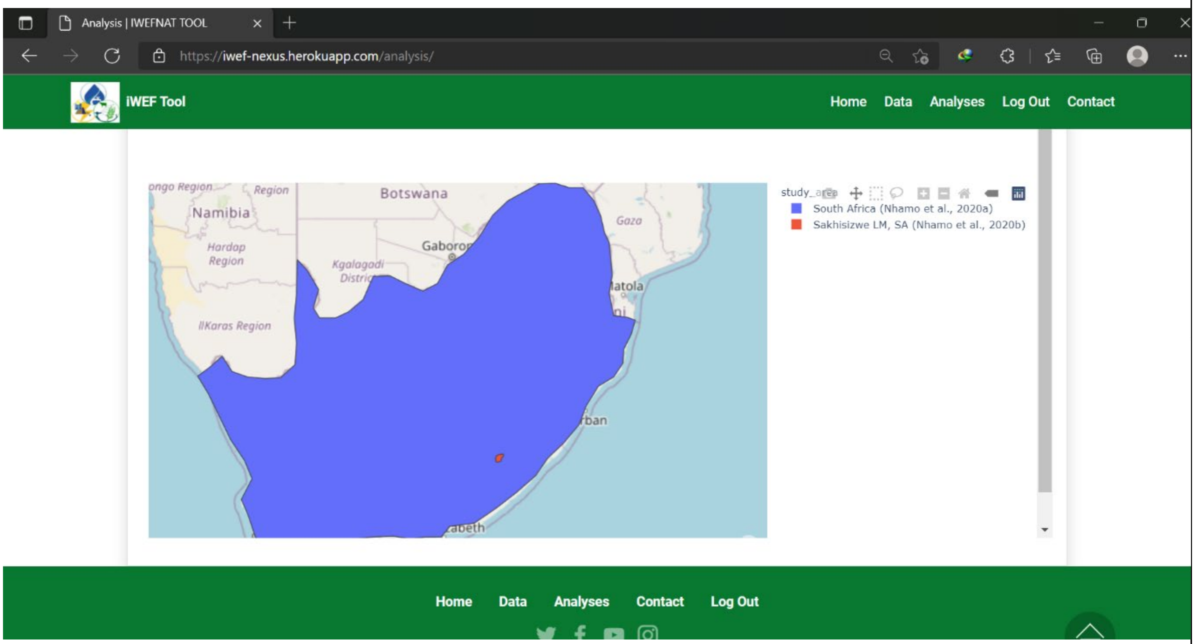
WEF nexus index	0-0.09	0.1-0.2	0.3-0.6	0.7-1
Sustainability	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable



Step 6: Multiple case studies

- Repeat steps 2-5 to prepare and upload data for multiple case studies.
- To display multiple results from many case studies, select multiple names of cases studies from your list in the *"Analyses"* section. In case of an invisible map among multiple results, click the name of map of interest in the map index and the hidden map will appear with other maps. Download these results as .png for exporting and reporting.





After the session, log out of your account by clicking the **'Logout'** tab.

Sample (prototype) data for iWEF model

Tables 3 and 4 present sample (prototype) consistent and inconsistent data for familiarizing with the CR concept in the iWEF model.

Table 3: A typical inconsistent pairwise comparison judgement dataset

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity
Water availability	1,00	1,00	1,00	0,33	0,33	1,00
Water productivity	1,00	1,00	3,00	5,00	1,00	1,00
Energy accessibility	1,00	0,33	1,00	3,00	0,20	0,33
Energy productivity	3,00	0,20	0,33	1,00	1,00	5,00
Food self-sufficiency	3,00	1,00	5,00	1,00	1,00	7,00
Cereal productivity	1,00	1,00	3,00	0,20	0,14	1,00

CR value = 0.31
Interpretation: 0.31 > 0.1 thus the pairwise comparison matrix is inconsistent

Table 4: A typical consistent pairwise comparison judgement dataset

Indicator Name	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity
Water availability	1,00	1,00	1,00	0,33	0,33	1,00
Water productivity	1,00	1,00	3,00	1,00	1,00	1,00
Energy accessibility	1,00	0,33	1,00	0,33	0,20	0,33
Energy productivity	3,00	1,00	3,00	1,00	1,00	2,00
Food self-sufficiency	3,00	1,00	5,00	1,00	1,00	7,00
Cereal productivity	1,00	1,00	3,00	0,50	0,14	1,00

CR value = 0.07
Interpretation: 0.07 < 0.1 thus the pairwise comparison matrix is consistent

Enquiries and help

- Click the 'Help' tab to access instruction manuals and video tutorials on how to use the iWEF tool.
- Sample data, results and interpretations are available as well.
- The data were extracted from previous related work by:
  i. Mabhaudhi et al. (2019) for Southern Africa (SADC) economic region at regional scale (https://dx.doi.org/10.3390/ijerph16162970),
  ii. Nhamo et al. (2020a) for South Africa country at national scale (https://doi.org/10.1016/j.envsci.2020.04.010), and
  iii. Nhamo et al. (2020b) for Sakhisizwe Local Municipality (in Eastern Cape Province, South Africa) at municipal scale (https://dx.doi.org/10.3390/su12208582).
- For further enquiries about iWEF, click the **'Contact'** tab, fill the form and click the **'Send'** tab. The iWEF system administrator will respond and address your issue.

Notes: The current version of iWEF can only process .csv and .geojson files for indicators table and shapefiles, respectively. Any other file formats will return errors.

Citing the iWEF model:

Cuthbert Taguta, Zolo Kiala, Tsitsi Bangira, Luxon Nhamo, Aidan Senzanje, Tafadzwanashe Mabhaudhi. 2022. *iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical model.*

Appendix 3: Dissemination Plan for iWEF

Press releases in Water Wheel (WRC), NdabaOnline (UKZN), and Farmers Weekly.

Journal article publications (see Appendix 4)

News and events updates sharing in partners' channels (UKZN-CTAFS and WRC) dedicated media and social channels including LinkedIn, YouTube, Facebook, Twitter, Instagram and SlideShare.

Leveraging future workshops of the WRC funded project C2019/2020-00007 (FROM THEORY TO PRACTICE: DEVELOPING A CASE STUDY AND GUIDELINES FOR WATER-ENERGY-FOOD (WEF) NEXUS IMPLEMENTATION IN SOUTHERN AFRICA) project in case study areas in South Africa and Zimbabwe will apply the iWEF modelling tool and act as dissemination platforms for the model.

Attending and presenting the iWEF tool in local and international academic gathering events such as WEF nexus Master Classes and Winter/Summer Schools, as well as symposia, workshops and conferences organized by International Commission on Irrigation and Drainage (ICID), SADC WaterNet, American Geophysical Union (AGU) and European Geosciences Union (EGU).

Capacity building at institutional level and the WEF nexus research community …

Appendix 4: Journal articles

Published journal articles

Taguta C, Senzanje A, Kiala Z, Malota M and Mabhaudhi T (2022) Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. *Front. Water 4:837316.* doi: 10.3389/frwa.2022.837316

frontiers in Water

SYSTEMATIC REVIEW
published: 25 March 2022
doi: 10.3389/frwa.2022.837316

Check for updates

Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review

Cuthbert Taguta [1,2], Aidan Senzanje [1], Zolo Kiala [2,3], Mphatso Malota [1,4] and Tafadzwanashe Mabhaudhi [2,5]*

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Sector-based resource management approaches partly contribute to the insecurities in water, energy and food sectors and resources. These approaches fail to acknowledge and capture the interlinkages between these connected resources, a key strength in the water-energy-food (WEF) nexus approach. However, the multi-centric, multidimensional, and spatiotemporally dynamic WEF nexus is complex and uncertain, thus requiring dedicated tools that can unpack it. Various sources have blamed the slow uptake and practical implementation of the WEF nexus on the unavailability of appropriate tools and models. To confirm those claims with evidence, literature on WEF nexus tools was searched from Scopus and Web of Science and systematically reviewed using the PRISMA protocol. It was found that the WEF nexus tools are being developed increasingly, with a current cumulative number of at least 46 tools and models. However, their majority (61%) is unreachable to the intended users. Some available tools are in code format, which can undermine their applicability by users without programming skills. A good majority (70%) lack key capabilities such as geospatial features and transferability in spatial scale and geographic scope. Only 30% of the tools are applicable at local scales. In contrast, some tools are restricted in geographic scope and scale of application, for example, ANEMI 3 and WEF models for large and household scales, respectively. Most (61%) of the tools lack wide application in actual case studies; this was partly attributed to the tools not being readily available. Thus, efforts should be made to disseminate and ensure end-users' uptake and application of developed tools. Alternatively, the user-friendly tools should be developed on-demand as requested and inspired by potential clients. Developers should consider utility, transferability and scalability across uses and users when improving existing tools and developing new tools so that they are adaptable, only requiring new, specific location-adapted inputs and data. Where and when it is necessary to capture spatial dynamics of the WEF nexus, tools should be geographic information system (GIS)-enabled for automatic WEF nexus location selection, geospatial mapping, and visualization. Such GIS-enabled WEF nexus tools can provide a bird's eye view of hotspots and champions of WEF nexus practices.

Keywords: water-energy-food nexus, model, format, GIS, scale, case study, implementation, availability

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Journal articles in preparation

Taguta C, Kiala Z, Bangira T, Nhamo L, Senzanje A and Mabhaudhi T (202x) Introducing iWEF 1.0: a web-based and GIS-enabled integrative water-energy-food (WEF) nexus analytical modelling tool.

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