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**Proceedings of the
International Workshop on Implementation of the
Water-Energy-Food (WEF) Nexus at different scales
for Socio-Economic Development**

**INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE
COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE**



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Proceedings of the

International Workshop on
***Implementation of the Water-Energy-Food (WEF) Nexus at different scales
for Socio-Economic Development***

Presented at:

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Editor

Prof. Dr Ragab Ragab

Workshop Chairman, President Hon. ICID and Chairman of the
Working Group on “Water-Energy-Food Nexus”

Fellow Principal Hydrologist and Water Resources Management Specialists at
UK Centre for Ecology & Hydrology, UKCEH, UK.

E-mail: rag@ceh.ac.uk and ragab@icid.org

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Preface



Water, energy and food are highly interconnected and critical to food security, poverty reduction, livelihoods, climate adaptation and mitigation, environmental and human health and biodiversity at different scales. Similarly, the Sustainable Development Goals (SDGs) have interdependence across goals and are linked to water, energy, food, and ecosystems. There is an urgency to adopt systematic approaches that can accelerate the implementation of the SDGs. However, governments, stakeholders, and investors are challenged to manage the water-energy-food-ecosystems nexus because of the complexities across the systems.

To investigate those challenges, the Working Group WEF-Nexus of ICID has organized five international workshops (Bali, Indonesia 2019, Adelaide, Australia 2021, Vizag, India 2023, Sydney, Australia 2024, Kuala Lumpur, Malaysia 2025) and this workshop in Marseille, France in 2026. The Working Group, in addition to these proceedings, produced three other proceedings:

- (1) Proceedings of the International workshop on the water-energy-food-nexus: implementation and examples of application, Vizag, India, 2023
https://icid-ciid.org/icid_data_web/25CongWorkshop-WFE-N.pdf
- (2) Proceedings of the International workshop on The Water-Energy-Food-Nexus: Applications & Impact on Societies, Environment and Ecosystem". Sydney, Australia
ISBN: 978-81-89610-44-9. 2024
https://icid-ciid.org/icid_data_web/wfen_proc_sydney2024.pdf
- (3) Proceedings of the International workshop on Implementation of the Water-Energy-Food (WEF) Nexus for Building Resilience, Adaptation, and Sustainable Socio-Economic Development' 2025. Kuala Lumpur, Malaysia
https://icid-ciid.org/icid_data_web/WIF4-ProcWS-WG-WFEN.pdf

The WEF nexus can be applied at different scales from city to region to national and transboundary scales. At the same time the benefits also depend on the scale of application. Thus, there is a need to understand and identify trade-offs and synergies across systems and scales to mitigate maladaptation and unintended consequences that jeopardize sustainability. For example, groundwater abstraction is critical for food security, but its overexploitation can inadvertently cause resource degradation, reduce water access and undermine ecosystem health across the scales. Identifying and understanding such tradeoffs can help the WEF Nexus to be an efficient approach to sustainable socio-economic development.

The incorporation of the socio-economic and cultural aspects in addition to technical approaches within the WEF nexus is necessary. It is also important to highlight farmers' perspectives: reducing farmers' vulnerability, improving their income, and allowing resource savings within the nexus application.

These proceedings highlight the interrelations of SDGs and how they are linked to the WEF Nexus. The aim is to develop an inclusive and integrated governance framework that drives towards the realization of the SDGs. The proceedings discuss the application of interactive modelling tools in basins of significant relevance and further focus on policy and governance mechanisms for implementing WEF solutions.

Subjects of the 2026 workshop and the proceedings included:

1. The impact and benefits of the WEF Nexus at different scales.
2. Approaches to bridge the gap between science, policy, and global initiatives within the WEF Nexus.
3. Solutions to integrate the socio-economic, cultural and technical aspects approaches within WEF Nexus.

4. WEF Nexus and farmers' perspectives: reducing vulnerability, improving income, and allowing resource savings.
5. How the current WEF Nexus models and frameworks can inform decision-making, and how to implement the WEF Nexus innovations and solutions.
6. WEF Nexus framework towards the realization of the SDGs.
7. The application of trade-offs and tools to assess the WEF Nexus index in basins.
8. Institutional and governance mechanisms to implement WEF solutions: WEF policy scenarios and operationalizing WEF Nexus.
9. Renewable energy for irrigation within the WEF Nexus in agriculture.
10. Women participation in WEF-Nexus implementation

The focus of the workshop and the proceedings was on examples of the application of the Nexus at different scales, the impact of Nexus application on societies, environment and ecosystems and the impact of Climate Change on the Water, Food and Energy WEF-Nexus.

Coordinators of the 2026 Workshop:

- ❖ Prof. Dr. Ragab Ragab, Workshop Chairman, President Hon. ICID, Chairman of the Working Group on “Water-Energy-Food Nexus” and Fellow at UK Centre for Ecology & Hydrology, UKCEH, UK (E-mail: ragab@icid.org)
- ❖ Dr. K. Yella Reddy, Vice President Hon. ICID and Vice-Chair of the WG on Water Energy-Food Nexus” and Officer on Special Duty, Government of Andhra Pradesh, India (E-mail: yellark@gmail.com)
- ❖ Dr. Ming-Che HU, Professor, Department of Bioenvironmental Systems Engineering, National Taiwan University. Secretary of the ICID WG-Nexus. mchu@ntu.edu.tw
- ❖ Dr. Sikka, Alok (IWMI-Delhi), Country Representative - India and Bangladesh / Senior Fellow at International Water Management Institute (IWMI), A.Sikka@cgiar.org
- ❖ Dr Mohamed AlHamdi, Senior Water and Land Officer for the Near East and North Africa. Food and Agriculture Organization of the United Nations (FAO) mohamed.alhamdi@fao.org
- ❖ Prof. Dr. Vinay Nangia, Research Program Leader – Soil, Water, and Agronomy, International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco. V.Nangia@cgiar.org



APPLYING THE WEF NEXUS INTEGRATIVE MODEL IN DATA-SCARCE AREAS: APPLICATIONS AT THE LOCAL LEVEL

Luxon Nhamo¹, Cuthbert Taguta², Sylvester Mpandeli³, Tinashe Dirwai⁴,
Stanley Liphadzi⁵, and Tafadzwanashe Mabhaudhi⁶

ABSTRACT

A constraint to operationalising the water-energy-food (WEF) nexus is the lack of organised, curated, standardised, accessible, compatible, and interoperable data. This has stalled the WEF nexus, impeding its progress from an abstract theory to a practical, analytical decision-support tool for integrated resource management. This study used the integrated WEF nexus analytical model to assess resource availability, distribution, use, and management in Sakhisizwe Local Municipality, a data-scarce local area in South Africa's Eastern Cape Province. The study employed a mixed-methods approach to gather data, including interviews with key stakeholders, a systematic literature review, and earth observation techniques. The results were key in informing strategic policy decisions and developing guidelines to improve the livelihoods of resource-poor rural communities. The model calculated a composite WEF nexus index of 0.185 with a deformed spider graph representing a marginally sustainable resource management outlook. The analysis clarified the interconnections of socio-ecological components, identified key intervention areas, and established quantitative relationships of related elements at the local level, based on reliable data. This facilitated an understanding of socio-ecological connections and sustainable livelihoods-environment co-benefits within the community, and the formulation of coherent adaptive strategies to alleviate poverty, a central goal of sustainable livelihoods.

Keywords: Sakhisizwe, WEF-Nexus indicators, nexus planning, resources availability and security

1. INTRODUCTION

Implementing the water-energy-food (WEF) nexus is hindered by a lack of reliable, consistent, and integrated data, which hampers the shift from theoretical models to practical decision-making tools (Naidoo et al., 2021). Current fragmented datasets, stored in siloed sectors, often delay the identification of trade-offs and synergies, the key elements for advancing sustainability and transformational goals. Bridging this gap *requires open*-access data platforms or repositories, standardised metrics, and shared, long-term data across sectors. This is especially important at the local level, where climate change impacts are more severe, and communities are vulnerable due to limited adaptive capacities (Mpandeli et al., 2019). Developing shared data platforms enables local communities to improve resource management, including trade-offs, and address vulnerabilities and context-specific challenges effectively. This is particularly critical for communities that rely on natural systems for their livelihoods. WEF nexus modelling depends on such datasets, as nexus approaches are based on the understanding that natural processes do not operate in isolation, and sustainable resource management relies on data from multiple sectors (Nhamo, Mabhaudhi, et al., 2020).

¹ Water Research Commission (WRC), Lynnwood Manor, Pretoria, South Africa; E-mail: luxonn@wrc.org.za

² Post-doctoral fellow. Centre for Transformative Agricultural and Food Systems, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa; E-mail: tagutac@ukzn.ac.za

³ Senior Research Manager. Water Research Commission (WRC), Lynnwood Manor, Pretoria, South Africa; E-mail: sylvesterm@wrc.org.za

⁴ Researcher. International Water Management Institute (IWMI), Harare, Zimbabwe; E-Mail: t.dirwai@cgiar.org

⁵ Group Executive. Water Research Commission (WRC), Lynnwood Manor, Pretoria, South Africa; E-mail: stanleyl@wrc.org.za

⁶ Prof of Climate Change and Food Systems, Centre on Climate Change and Planetary Health, London School of Hygiene and Tropical Medicine (LSHTM), London, UK, E-mail: tafadzwanashe.mabhaudhi@lshtm.ac.uk

The WEF nexus integrative model is a systems-based framework designed to break down "siloeled" resource management by analysing the interdependencies, synergies, and trade-offs between WEF sectors. It provides evidence-based decision-making tools to ensure sustainable resource use, particularly in the context of climate change and rising demand, using the Analytic Hierarchy Process (AHP) (Nhamo, Mabhaudhi, et al., 2020; Taguta et al., 2023). The integrative model is essential for promoting sustainable, equitable, and secure resource management, particularly in regions facing high vulnerability. Applying the model in data-scarce, local-level areas involves a shift from complex, data-intensive quantitative modelling to flexible, qualitative, and participatory approaches, including Earth Observation methods, interviews, and literature review (Richelle et al., 2025). In regions with limited data, such as Sakhisizwe Municipality in the Eastern Cape Province of South Africa, the WEF nexus approach relies on mapping interdependencies, leveraging qualitative expert knowledge, and creating context-specific indicators (Nhamo, Ndlela, et al., 2020).

Participatory mapping is a critical tool for bridging data gaps in data-scarce regions, particularly in understanding the complex, interconnected nature of Water-Energy-Food (WEF) systems (Nikolaidis et al., 2025). It utilizes local, citizen science, traditional, and indigenous knowledge to map causal relationships, such as how agricultural practices (food) impact water quality (water) or how pumping systems (energy) affect water availability (de Carvalho et al., 2021). By engaging local stakeholders, this method captures spatial and social nuances often missed by top-down, national-level data collection techniques (Nikolaidis et al., 2025). This is a key to replacing complex input-output data flows through identifying the most critical links to support decision-making. Modelling complex WEF nexus data flows through input-output analysis enables the identification of critical interlinkages, such as energy-intensive water pumping for irrigation, to manage trade-offs and enhance synergies (Wang et al., 2026). By quantifying these flows, decision-makers can pinpoint "hotspots" where interventions, such as transitioning to gravity-fed irrigation or optimising pumping, yield the highest returns and promote resource-use efficiency. Remote sensing and Geographic Information Systems (GIS) tools are critical in filling the "missing" WEF data gaps, particularly by providing long-term, consistent monitoring of natural resources that traditional ground-based measurements often fail to capture (de Carvalho et al., 2021). By analysing satellite data, these technologies assess historical and current trends, which are essential for managing the interconnected WEF sectors.

This study applied the integrated WEF nexus analytical model, an AHP-based model, to holistically assess resource availability, distribution, use, and management in Sakhisizwe Local Municipality in the Eastern Cape Province of South Africa. Sakhisizwe is a data-scarce local area, dominated by subsistence smallholder farmers who rely on natural resources for their livelihoods (Nhamo, Ndlela, et al., 2020). The study used a mixed-methods approach, including key informant interviews, a systematic literature review, and participatory earth observation techniques to collect data for use in the WEF nexus integrative analytical model (Nhamo, Mabhaudhi, et al., 2020). The data collection methods in this study are essential sources of information that provide necessary insights to assess and improve livelihoods in regions with limited data, making this approach replicable.

2. METHODS

2.1. Description of the study area

Sakhisizwe Municipality is in the Chris Hani East District of the Eastern Cape Province of South Africa Fig. 1, with an area of 2,556 km². It is made up of a gently undulating "tableland" forming the Drakensberg foothills, with elevation ranging between 750 m and 2,600 m (IDP, 2015). In recent years, the area has experienced extreme flooding and snow (Ndlovu et al., 2021). The rocky and undulating landscape makes it difficult for smallholder farmers to be productive and be food secure. The highly variable elevation shapes the soil types, with low-lying areas characterised by clay content (highly erodible), and the surrounding hills consist of strong [Lithosols](#) soils. It receives an annual average rainfall of between 600 mm and 1,000 mm (IDP, 2015). The vegetation is mainly sweet and sour Grass found in the plain veld. Trees and shrubs occur on sheltered sites, rocky hills, and ridges. Dohne Sourveld is the most common transitional vegetation and shrub type, and the sweet grass is dominated by Red grass *Themeda triandra*. Unimproved Grassland makes up (76%), with Cultivated Dry land (9%),

Degraded Unimproved Grassland (6%), Forest Plantations (2.5%), Thicket Bushland (2.2%), and Built-Up Areas (1%) making up the balance (IDP, 2015). The grasslands are the main source of grazing livestock.



Fig. 1. Location of the Sakhisizwe Municipality in South Africa

The municipality has a diverse, multi-racial population of about 63,582 people, residing mostly in rural areas and clustered in the former homeland, formerly known as the Transkei, which is well known for unproductive conditions, leading to extreme poverty (IDP, 2015). The population is largely rural, comprising of 61% rural population and 39% urban. The land use is shaped by the historical setup, with vast fertile lands under commercial farming, while the majority reside in unproductive lands of the former Transkei (van Koppen et al., 2017). As a result of these socio-economic inequalities, communities residing in this former homeland face extreme weather events, yet research is limited due to poor data collection.

2.2. Data collection and analysis

Applying the WEF nexus integrative model and its online version, the iWEF, in data-scarce, local-level contexts requires moving away from data-intensive, top-down modelling towards flexible, mixed-methods approaches (Nhamo, Mabhaudhi, et al., 2020; Taguta et al., 2023). This shift prioritises qualitative insights, participatory engagement, and emerging technology to understand local resource interdependencies, especially in regions with limited local-level datasets. The methods used to collect data for this data-scarce local area are given in Table 1.

Table 1. Mixed-methods approaches for data collection in data-scarce local areas

Data collection methods	Description of the approaches
Qualitative and participatory approaches	- Stakeholder engagement that includes stakeholder dialogues or interviews to identify key nexus challenges, validate information, and define resource trade-offs, transforming complex interactions into actionable, context-specific knowledge. - Causal loop diagrams (CLDs) are important for visualising complex interlinkages (bilateral and circular) between WEF sectors, mapping the system's dynamics, even without extensive quantitative data. - Qualitative mapping, in-depth interviews, and expert consultations provide qualitative data on community perceptions of resource interdependencies, identifying hotspots where nexus, rather than sectoral, planning is required. - Literature and document review, including technical reports, academic studies, and policy documents, are an important source of information to fill data gaps.
Utilizing Earth Observation methods	- Remote Sensing (RS) applications, particularly satellite data, provide a cost-effective alternative for monitoring and gathering data on water availability, land-use changes, and agricultural productivity where ground monitoring is absent. - The Google Earth Engine (GEE) platform allows for cloud-based processing of over 40 years of Earth Observation data to generate time-series analyses for local sites, providing insights into trends like vegetation change and water usage. - Biomass and Climate Data: Earth observation is used to assess biomass and climate data required in nexus linkages related to agriculture, water availability, and land-use change, assisting.
Integrated modelling in data-scarce contexts	- Iterative modelling and proxies include, instead of fully data-driven models, studies that use available global data and proxy indicators to approximate local situations. This often involves applying a "data hierarchy" to identify the best available information. - Qualitative-to-Quantitative mapping is a process that often begins with qualitative mapping of links, followed by the quantification of key, identified critical links to understand the scale of the challenge. - SWOT matrix spatialisation involves combining field data collection with participatory mapping to identify strengths, weaknesses, opportunities, and threats to resource security. - Community-based system dynamics (CBSD) is an approach that focuses on engaging community members in defining the problem and designing solutions.

This adaptive, bottom-up approach enables the application of the WEF nexus to improve local livelihoods and provide actionable evidence for decision-makers in resource-constrained environments.

2.3. The indicators for which the data is required

The analytical WEF nexus integrative model is a multi-criteria decision method (MCDM) that uses the Analytic Hierarchy Process (AHP). The model focuses on sustainability indicators that speak to water, energy, and food security (Nhamo, Mabhaudhi, et al., 2020). The model analyses the complex interconnections and dynamics among the WEF sectors, mathematically depicting the relationships between inputs and outputs within a livelihood-environment system. The main outcomes of a socio-ecological system include sustainable livelihoods and healthy ecosystems (Connell, 2010). The numerical representation facilitates classifying a system as either sustainable or unsustainable (Nhamo, Mabhaudhi, et al., 2020). The outcomes are dependent on the balance between human demands and natural supply. Sustainability indicators (Table 2) form the basis for establishing numerical relationships among the WEF sectors.

Table 2. Sustainability indicators and to quantify WEF nexus interactions.

WEF Sector	Indicator	Units
Water	Proportion of available freshwater resources per capita (availability)	m ³ /capita
	Proportion of crops produced per unit of water used (productivity)	\$/m ³
Energy	Proportion of the population with access to electricity (accessibility)	%
	Energy intensity measured in terms of primary energy and GDP (productivity)	MJ/GDP
Food	Prevalence of food insecurity in the population (self-sufficiency)	%
	Proportion of sustainable agricultural production per unit area (cereal productivity)	kg/ha

Source: Nhamo et al., 2020

The MCDM provides indices for each indicator, which can be shown on a spider graph to give an overview of resource management and indicate priority areas for intervention (Nhamo, Mabhaudhi, et al., 2020).

2.4. Calculation and normalization of indices

The indicators (Table 2) are used to establish numerical relationships among the indicators through a comparison matrix by indexing them. Each indicator is compared with the others by assigning a value (index) according to Saaty's AHP pairwise comparison matrix (PCM) and then normalizing (Saaty, 1987; Saaty, 1977). Through the PCM, the AHP calculates the index for each indicator by taking the eigenvector (a vector whose direction does not change even if a linear transformation is applied) corresponding to the largest eigenvalue (the size of the eigenvector) of the matrix and then normalising the sum of the components (Thomas & Stewart, 2011). 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 as the priority weight vector. In the eigenvector method, the priority weight vector is set to the right principal eigenvector w of the pairwise comparison matrix A . Therefore, the eigenvector method is to find the maximum value λ and its corresponding vector w , such that (Saaty, 1990):

$$Aw = \lambda w \quad (1)$$

The overall importance of each indicator is then determined. The basic input is the pairwise matrix, A , of n criteria, according to Saaty's scaling ratios, which is of the order $(n \times n)$ (Saaty, 1977). A is a matrix with elements a_{ji} . The matrix generally has the property of reciprocity, expressed mathematically as:

$$a_{ij} = \frac{1}{a_{ji}} \quad (2)$$

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} , expressed as:

$$b_{ij} = \frac{a_{ij}}{\sum_{j=1}^n a_{ji}} \quad (3)$$

Each weight value w_i is computed as:

$$w_i = \frac{\sum_{j=1}^n b_{ji}}{\sum_{i=1}^n \sum_{j=1}^n b_{ji}}, i, j = 1, 2, 3 \dots, n \quad (4)$$

The integrated WEF nexus index is then calculated by taking the median of all indicator indices. This integrated composite index reflects the overall performance of resource management collectively.

2.5. Determining the consistency of the pairwise comparison matrix

The AHP-derived indices must always be consistent to an acceptable ratio of less than 0.1 or 10% (the allowable consistency). The consistency ratio (*CR*) indicates the likelihood that the matrix judgments were generated randomly and are consistent (Alonso & Lamata, 2006). Higher *CR* values indicate inconsistency, while smaller values represent consistency and must be re-evaluated (Saaty, 1977). The *CR* is calculated as (Franek & Kresta, 2014):

$$CR = \frac{CI}{RI} \quad (5)$$

where: *CI* is the consistency index, *RI* is the random index, and the average of the resulting consistency index depending on the order of the matrix given by Saaty (Saaty, 1977). *CI* is calculated as:

$$CI = \gamma - \frac{n}{n-1} \quad (6)$$

where: γ is the principal eigenvalue (shaded section of Table 4), and *n* is the number of criteria or sub-criteria in each pairwise comparison matrix.

3. RESULTS AND DISCUSSION

3.1. The pairwise comparison matrix for Sakhisizwe Municipality

The PCM determines the relationship of WEF sectors. The diagonal elements represent the values of unity (i.e., when an indicator is compared with itself, the relationship is 1) (Table 3). Since the matrix is symmetrical, only the upper half of the triangle (grey-shaded) is filled in, and the remaining upper cells are reciprocals of the lower triangle. The WEF nexus-based PCM for Sakhisizwe Municipality is given in Table 3. The diagonal numbers are unity values (i.e., when an indicator is compared with itself, the relationship is always 1). As the PCM is symmetrical, only the upper triangle (grey rows) is determined, and the lower unshaded triangle represents the reciprocals. The matrices are established using a scale from 1/9 to 9, where 1/9 indicates the lowest and most insignificant relationship, and 9 represents the highest and most significant relationship (Saaty, 1977).

Table 3. Pairwise comparison matrix for WEF nexus indicators in Sakhisizwe Municipality

Indicator	Pairwise comparison matrix					
	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Cereal productivity
Water availability	1	1/3	1	1/7	1/6	1
Water productivity	3	1	3	5	1	1
Energy accessibility	1	1/3	1	1/2	1/3	1/5
Energy productivity	7	1/5	2	1	3	5
Food self-sufficiency	6	1	3	1/3	1	7
Cereal productivity	1	1	5	1/5	1/7	1

3.2. Normalized pairwise comparison matrix for WEF nexus indicators

The normalised indices presented in Table 3 are shown in Table 4, where each index is calculated using Equations 3 and 4, respectively. The sum of these indices should always be 1, as indicated in the last column of Table 4. This summation demonstrates that the indicators are numerically linked or related and can be analysed as a cohesive whole. The *CR* for the normalised pairwise matrix is 0.09, which

falls within the acceptable range. The weighted average of the calculated indices constitutes the WEF nexus integrated index, categorised as shown in Table 5.

Table 4. Normalised pairwise comparison matrix and composite indices

Indicator	Water availability	Water productivity	Energy accessibility	Energy productivity	Food self-sufficiency	Crop productivity	Indices
Water availability	0.053	0.086	0.067	0.020	0.030	0.066	0.053
Water productivity	0.158	0.259	0.200	0.697	0.177	0.066	0.259
Energy accessibility	0.053	0.086	0.067	0.070	0.059	0.013	0.058
Energy productivity	0.368	0.052	0.133	0.139	0.532	0.329	0.259
Food self-sufficiency	0.316	0.259	0.200	0.046	0.177	0.461	0.243
Crop productivity	0.053	0.259	0.333	0.028	0.025	0.066	0.127
CR = 0.09							$\Sigma = 1$
Composite WEF nexus index (weighted average)							0.185

The indices are ranked according to their respective weights, with the highest ranked as 6 and the lowest as 1, to compute the weighted average. The composite index for Sakhisizwe Municipality is 0.185, which classifies the municipality as marginally sustainable (Nhamo et al., 2020). The indices range from 0 to 1, where 0 represents unsustainable resource management, and 1 represents highly sustainable resource management (Table 5).

3.3. Classification categories for indicators and the WEF nexus integrated index

The classification categories (Table 5) represent the resource management categories, which are essential for determining the intensity and importance of indicators (Nhamo, Mabhaudhi, et al., 2020).

Table 5. WEF nexus indicators performance classification categories

Indicator	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
Water availability (m³/per capita)	< 1 700	1 700 – 6 000	6 001 -15 000	> 15 000
Water productivity (US\$/m³)	< 10	10 - 20	21 - 100	> 100
Food self-sufficiency (% of pop)	> 30	15 - 29	5 - 14	< 5
Cereal productivity (kg/ha)	< 500	501 – 2 000	2 001 – 4 000	> 4 000
Energy accessibility (% of pop)	< 20	21 - 50	51 - 89	90 - 100
Energy productivity (MJ/GDP)	> 9	6 - 9	3 - 5	< 3
WEF nexus composite index	0 - 09	0.1 - 0.2	0.3 - 0.6	0.7 - 1

Source: Nhamo et al., 2020

3.4. Interpretation of the indices

The indices are visually represented in a spider graph (Fig. 2), which provides a clearer and simplified overview of the numerical relationships among the indicators. The spider graph illustrates the interactions and interdependencies of the WEF sectors, providing an integrated overview of resource management. The deformed shape of the centrepiece (Fig. 2) indicates an imbalanced resource management. The further an index is from the centre of the spider graph, the better the level of sustainable management. In contrast, the closer it is to the axis, the more it signifies unsustainable

management. Therefore, the representation of the indices numerically unbundles the complex interlinkages between WEF sectors.

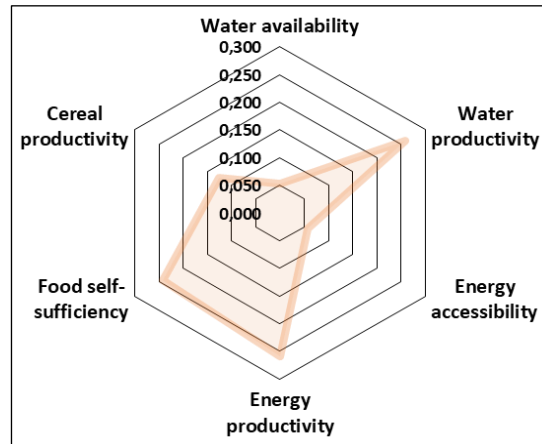


Fig. 2. Performance of WEF nexus indicators in Sakhisizwe Municipality in 2018

There is a high level of water and energy productivity (both at 0.259) in Sakhisizwe Municipality, followed by food self-sufficiency (0.243). The enhanced water efficiency in the municipality may result from limited water resources or low availability (0.053), leading to more careful and efficient usage. Although energy production is high, accessibility is very low (0.058), because 21% of the population has no access to electricity. The situation is worsened by the depleting water resources, which compromise hydro-electricity generation, the main source of energy (IDP, 2015). Similarly, extreme droughts in the municipality highlight low water availability, which is affecting energy accessibility and cereal productivity. Water management needs to be improved to ensure water, energy, and food security in a municipality where 61% of the population lives in rural areas, where climate change vulnerabilities are very high (IDP, 2015). Overall, an integrated composite index of 0.185 classifies the municipality as marginally sustainable, according to Nhamo's classification (Nhamo et al., 2020).

4. DISCUSSION

The deformed shape of the spider graph centrepiece (Fig. 2) indicates an imbalanced resource management. A balanced economy and sustainable resource management are achieved when the centrepiece achieves a circular shape. The circular shape is best when all indicators reach the highest index achieved in water productivity and energy productivity (0.259). Thus, nexus planning informs policy and decision-making on interventional strategies to prioritise developmental initiatives. The approach also serves as a platform for stakeholder engagement, aiming to harmonise strategies and policies. It functions not only as an analytical, conceptual, and discourse framework but also as a collaborative tool (Nhamo, Mabhaudhi, et al., 2020). Current sectoral approaches only exacerbate current challenges associated with climate change and increase the vulnerability of communities.

Achieving a circular shape of 0.259 across all indicators will result in balanced resource management and help the municipality attain a moderately sustainable classification. A circular shape indicates effective resource management practices. Therefore, the WEF nexus analytical model provides decision-makers with a framework that integrates strategic policies that enhance resource-use efficiency. Consequently, the analytical model is a vital decision-support system for monitoring resource utilisation and performance, as it highlights the interactions among different sectors. It plays a crucial role in setting developmental targets and achieving the objectives outlined in the Integrated Development Plan (IDP), National Development Plan (NDP), and relevant Sustainable Development Goals (SDGs). For policymakers and decision-makers, the model serves as a guiding tool to promote sustainable resource management, particularly for:

- Establishing quantitative relationships and simplifying the complex connections between water, energy, and food resources, while ensuring livelihood security.
- Identifying trade-offs and synergies within socio-ecological systems and developing informed strategies to achieve sustainable livelihoods and enhance resilience.
- Ensuring a balance between human demands and the supply of natural resources to maintain livelihood sustainability.
- Making timely interventions in priority areas to reduce pressures and stresses on the system.
- Providing tools to monitor progress and foster a sustainable socio-ecological system.
- Offering transformative solutions to complex socio-ecological challenges from a nexus planning perspective.

Importantly, applying the WEF nexus integrative model in data-scarce, local-level settings has shown success by shifting from purely quantitative, large-scale modelling to qualitative and semi-quantitative approaches that prioritise community-led, practical interventions. This is critical for local areas as climate change is generally felt more at the local level, particularly in rural communities where adaptation is low (Atkinson & Atkinson, 2023). This makes localised action and enhanced local strategies, particularly in vulnerable, low-adaptation rural areas, a critical component of climate change adaptation strategy. While data limitations exist, this study has shown that integrating local context with tools like the AHP and stakeholder mapping can identify, quantify, and manage critical resource interlinkages. The study has demonstrated a four-step operational approach, which suggests a practical framework represented by: (a) qualitatively mapping WEF links, (b) quantifying key links using available data, (c) identifying critical links, and (d) leveraging results for project design.

5. CONCLUSIONS

The results are key in informing strategic policy decisions and developing guidelines to improve the livelihoods of resource-poor rural communities, even in data-scarce areas. The model calculated a composite WEF nexus index of 0.185 with a deformed centrepiece of the spider graph. The deformed spider graph represents marginally sustainable resource management. The analysis clarified and simplified the connections between socio-ecological components and helped identify key intervention areas. The results demonstrate the level of interlinkages of the socio-ecological system by establishing quantitative relationships among related elements, even at the local level. The data used is reliable because it was sourced from participatory and citizen science research. The results facilitate an understanding of socio-ecological connections and sustainable livelihoods-environment co-benefits within the community, and the formulation of coherent adaptive strategies to alleviate poverty, a central goal of sustainable livelihoods. This was crucial in developing context-specific transformative pathways at the local level, which were used to guide policy aimed at improving livelihoods. The effective application of the WEF nexus integrative analytical model at a local scale underscores the relevance of the WEF nexus approach across different spatial levels, particularly at the local scale, where the impacts of climate change are most strongly felt. Overall, a successful WEF nexus application in data-poor scenarios lies in prioritising local-level, participatory approaches that convert available data, even if qualitative, into actionable, sustainable management plans.

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EMBEDDING WEFE NEXUS THINKING IN DECISION-MAKING WITH WATNEX

Tania Imran¹, Gijs W. H. Simons², Heba AlHariry³, Mohamed AlHamdi⁴, and Peter Droogers⁵

ABSTRACT

Decision-making within the Water-Energy-Food-Ecosystem (WEFE) nexus is constrained by fragmented analytical approaches and limited tools that integrate cross-sectoral dynamics. Under the inter-Regional Technical Platform on Water Scarcity (iRTP-WS) and the Regional Water Scarcity Initiative (WSI), the WatNEX (Water Accounting for Nexus Decision-making) tool has been developed as a flexible water accounting engine supporting nexus-based assessments. WatNEX uses the Water Evaluation and Planning (WEAP) system as its computational backbone, complemented by a custom plugin that introduces energy, food, and ecosystem variables into the simulation environment and extracts outputs to a macro-enabled Excel interface. Unlike retrospective frameworks, it incorporates scenario-based assessments, enabling users to explore future projections and management interventions and to quantify trade-offs and synergies across sectors. WatNEX has been demonstrated in two diverse river basins: the Tuul (Mongolia) and the Lower Medjerda (Tunisia), representing a range of hydro-climatic, socio-economic, and data availability contexts.

Results highlight the tool's value in diagnosing system imbalances and revealing cross-sectoral interactions. In Mongolia's Tuul River Basin, where irrigated agriculture covers only a limited area but urban domestic and industrial demands compete sharply for scarce surface water, WatNEX quantified sectoral water shortages exceeding 48% under baseline conditions. Scenario analyses showed that groundwater abstraction could reduce unmet domestic demand by 36%, but at the cost of significantly higher energy consumption and increased ecosystem degradation, a trade-off invisible to single-sector analyses. In Tunisia's Lower Medjerda Basin, a 20% land-use conversion toward irrigated agriculture increased water shortages by 1.6% while yielding only a 1% gain in food production due to existing water scarcity, highlighting the limitations of irrigation expansion without corresponding supply augmentation. A desalination scenario reduced unmet demand by 6% but raised energy consumption by 5.7%, illustrating the importance of WEFE-integrated planning for non-conventional water strategies.

Keywords: Water-energy-food-ecosystem WEFE Nexus, Water accounting, WEAP, WatNEX

1. INTRODUCTION

Over the last decade, the nexus of water, energy, food, and ecosystems (WEFE) has been recognised as a tightly coupled system essential for global development and human well-being (Sušnik & Staddon 2022). Actions in one resource sector have direct implications in others, yet the complexity of these interactions across scales makes impacts and feedback difficult to quantify. Despite growing conceptual recognition, nexus methods frequently fall short of capturing the very interlinkages they aim to address, and many remain confined to disciplinary silos (Albrecht et al. 2018). Specific, reproducible methods for integrated nexus assessment remain uncommon.

¹ Water Management Expert, FutureWater. Costerweg 1V, 6702 AA, Wageningen, The Netherlands. E-mail: t.imran@futurewater.nl

² Managing Director, FutureWater. Costerweg 1V, 6702 AA, Wageningen, The Netherlands. E-mail: g.simons@futurewater.nl

³ Land and Water Officer, Food and Agriculture Organization of the United Nations (UN FAO). 11 El Eslah El Zerai Str. (near Agricultural Museum), Dokki, Cairo, Egypt. E-mail: heba.alhariry@fao.org

⁴ Senior Land and Water Officer, Food and Agriculture Organization of the United Nations (UN FAO). 11 El Eslah El Zerai Str. (near Agricultural Museum), Dokki, Cairo, Egypt. E-mail: mohamed.alhamdi@fao.org

⁵ Senior Hydrologist, FutureWater. Costerweg 1V, 6702 AA, Wageningen, The Netherlands. E-mail: p.droogers@futurewater.nl

Most existing frameworks acknowledge that external factors (climate change, population dynamics, and socio-economic development) must be considered when managing WEFE resources in an integrated manner (Purwanto et al. 2021). Growing regional and global variation in natural resource distribution creates a need for models that incorporate these drivers to support planning and policy processes. Such models should be flexible enough to operate at varying geographic levels, from national to watershed and project scales (Shannak et al. 2018).

Principal challenges in nexus modelling include assembling detailed input data for spatially and temporally explicit models (Shannak et al. 2018) and establishing a common basis to evaluate resources across sectors. These resources are subject to exogenous parameters that vary over time and space, including population growth, migration, and regional economics (Liu et al. 2017). Few water-energy-food planning approaches have incorporated spatial cropping patterns and land use alongside energy and water requirements.

To address these challenges, the WatNEX (Water Accounting for Nexus Decision-Making) tool was developed under the FAO inter-Regional Technical Platform on Water Scarcity (iRTP-WS). The iRTP-WS builds on the Water Scarcity Initiative (WSI) launched in 2013 by the FAO Near East North Africa region to address water challenges exacerbated by climate change, population growth, and unsustainable resource management. The 2024-2025 theme, "*Integrated Water Solutions: Navigating Climate Change and WEFE Nexus Dynamics*", emphasises nexus-based solutions that promote inclusive, cross-sectoral decision-making.

WatNEX was designed to address these challenges in an integrated way, by acknowledging water as a key enabler of the WEFE nexus (Sušnik et al. 2023) and accounting for both resource demand and availability, which traditional water-accounting frameworks do not. Unlike retrospective accounting frameworks, it also supports scenario-based analysis, enabling users to explore future projections and management interventions and to quantify trade-offs and synergies across sectors. By building on the widely used Water Evaluation and Planning (WEAP) model, developed by the Stockholm Environment Institute, and exporting results to an Excel-based interface, WatNEX remains globally applicable, reproducible, and accessible to technical specialists, researchers, practitioners, and policymakers.

This paper presents the development and demonstration of WatNEX across two contrasting river basins: the Tuul River Basin in Mongolia and the Lower Medjerda Basin in Tunisia. These pilot applications test the tool's flexibility under different modelling pathways, data availability conditions, and socio-hydrological contexts, and illustrate its capacity to generate actionable nexus insights for water resource planning.

2. METHODS

2.1 WatNEX Toolkit and Workflow

WatNEX was developed to apply water accounting to nexus decision-making, enabling users to quantify resource availability and consumption across both time and space. The toolkit uses WEAP as its computational engine for generating water-accounting components. Building on the Rapid Evaluation of the Water, Energy, Food, Ecosystem nexus (REWEFe) tool, a dedicated WatNEX plugin for WEAP was developed to integrate energy, food, and ecosystem data. This plugin quantifies interlinkages among the four sectors for each region (nexus unit) defined by the user in WEAP and exports the results to WatNEX via Visual Basic Applications (VBA) scripts (Figure 1).

Within the ecosystem domain of the tool, water and energy system changes are translated into ecosystem values that are expressed in monetary terms, for unified reporting. The main parameters include the value of natural-area extent, environmental flow value associated with river outflows, and CO₂-equivalent emissions per kilowatt-hour of electricity generated from non-renewable sources, with the underlying relationships quantified from literature.

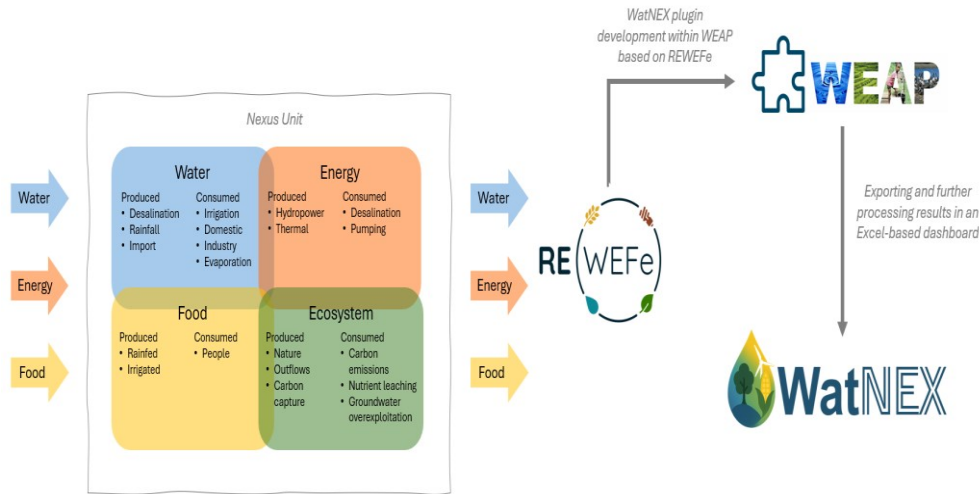


Figure 1. Water-Energy-Food-ecosystem linkages included in the development of WatNEX.

Because many stakeholders are already familiar with Microsoft Excel, WatNEX was designed as a macro-enabled platform. Users visualise water accounts, nexus balances, and scenario outcomes by importing WEAP results into WatNEX and browsing through the tabs.

To test the applicability of the tool across different contexts, two pilot basins were selected (Table 1). A consistent three-step analytical workflow was applied across both cases:

- **Preparing WEAP models in line with WatNEX requirements:** Existing WEAP models were adapted, or new models set up, to ensure compatibility with the WatNEX accounting structure. Each region is represented by a catchment node subdivided into irrigated agriculture, rainfed agriculture, natural vegetation, and other land uses, complemented by domestic and industrial demand nodes as well as a supply node for entering the energy, food and ecosystem inputs.
- **Building scenarios within WEAP:** Basin-specific projection and intervention scenarios were developed to illustrate how the tool supports nexus-oriented assessments through quantifying synergies and trade-offs.
- **Analysing outputs in WatNEX:** Using custom-built scripts, the WatNEX plugin exported water accounts, WEF resource dynamics and results of the scenarios developed to the WatNEX dashboard.

Table 1. Overview of the two pilot basins selected for WatNEX application.

Basin	Country	Area (km ²)	Status of existing models
Tuul River Basin	Mongolia	49,773	New WEAP model built from scratch; no prior models available
Lower Medjerda Basin	Tunisia	~23,000	Existing operational WEAP model restructured for WatNEX compatibility

The case studies were built using publicly available remotely sensed data, including Dynamic World land cover (Brown et al. 2022), NASA LGRIP irrigated-area mapping (Teluguntla et al. 2023), CHIRPS precipitation (Funk et al. 2015), and ERA5-Land reanalysis (Muñoz-Sabater et al. 2021), to maximise reproducibility. Where required, secondary sources such as official river basin reports and research articles were used to fill data gaps.

2.2 Case Study: Tuul River Basin (Mongolia)

The Tuul River Basin covers 49,773 km², spanning seven districts of Ulaanbaatar city and 37 soums (the second-level administrative district in Mongolia) across five provinces. The river runs 717 km and supplies nearly half of Mongolia's national domestic water, owing to the large population concentrated in Ulaanbaatar, which is home to approximately 45% of the country's total population. The elevation ranges from 770 to 2,800 metres above sea level. The basin has a continental climate with average annual precipitation of 251-300 mm (concentrated in summer) and mean temperatures ranging from -20 to +20°C, with the annual average near 0°C. Annual runoff constitutes approximately 69% of total river discharge, followed by groundwater (25%) and snowmelt (6%) (Dolgorsuren et al. 2012).

The basin faces interconnected WEFE challenges. Increasing wastewater discharges from industrial and domestic sources continue to degrade surface water quality. Moreover, the high reliance on thermal power plants, which require considerable amounts of water for cooling, adds pressure on the limited water resources in the basin. Rapid urbanization, centred in and around Ulaanbaatar city, combined with overgrazing, contributes to land degradation, adversely impacting ecosystem services.

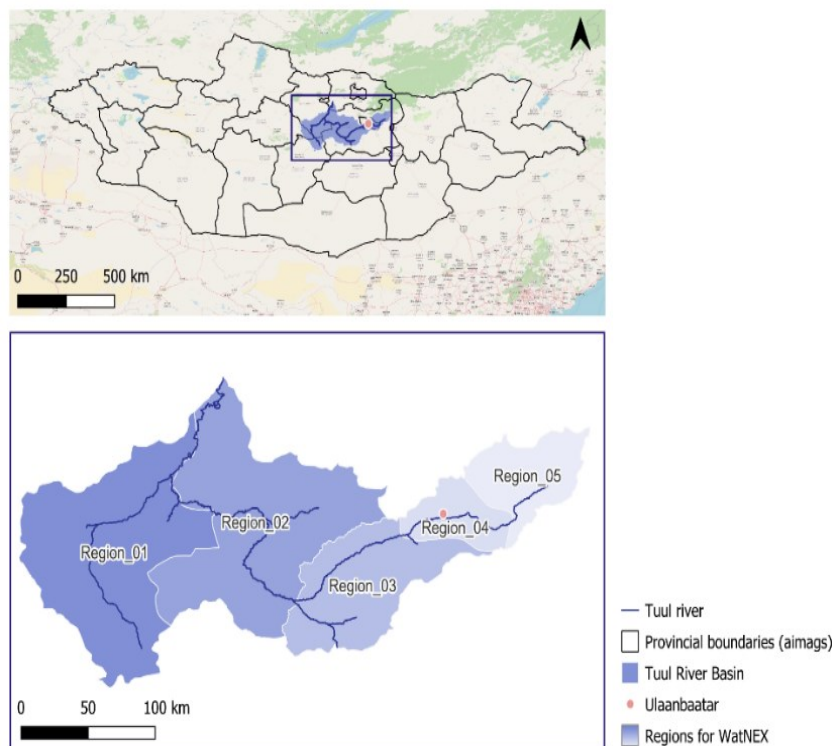


Figure 2. Regions defined within the Tuul River Basin for WatNEX analysis, delineated at the intersection of provincial and hydrological boundaries.

As no prior WEAP model existed, a new model was developed, testing WatNEX's compatibility with a fully new setup in a data-scarce environment. The basin was subdivided into five regions delineated based on the intersections of administrative and hydrological boundaries (Figure 2). For each region, a domestic, industrial, and catchment node was defined. The Tuul River was constructed in five corresponding segments, with each segment receiving inflow from catchment runoff and residual flows from upstream. Livestock demands were incorporated within domestic demand sites and irrigated agriculture within the catchment node. The land use classes, derived from the Dynamic World (Brown et al. 2022) and LGRIP (Teluguntla et al. 2023) datasets, were recategorized as per WatNEX requirements.

Based on the nexus challenges in the basin, three scenarios were developed to assess impacts across the four nexus domains:

- An annual population growth rate of 1.5% was applied to region 4 (Ulaanbaatar) based on the UN World Population Prospects 2024 projections to 2040, while all other demand nodes retained baseline population.
- As global climate models show an increase in precipitation across Mongolia until the end of the century, CMIP6 precipitation projections under SSP2-4.5 for the 2020–2039-time horizon were extracted. The median delta (ratio of projected to historical precipitation) varied by month, ranging from approximately 1.01 in summer (June-August) to 1.27 in late winter (February), with an annual median of about 1.12, indicating a roughly 12% increase in precipitation. These monthly ratios were applied to historical precipitation and phased in linearly from no change (baseline) in 2020 to their full value by 2039 across the five catchments.
- While groundwater, as a source, was kept inactive in the baseline, it was linked as a supply source for domestic demands in region 4. This scenario, unlike the other two, represents an intervention rather than a projection. The maximum theoretical aquifer capacity was set at 637.7 million cubic meters (MCM) and maximum withdrawal at 141.8 MCM (Dolgorsuren et al. 2012).

2.3 Case Study: Lower Medjerda Basin (Tunisia)

The Lower Medjerda River Basin is one of Tunisia's most important hydrological and socio-economic regions, situated in the northeast of the country. The Medjerda River, the only perennial river in Tunisia, originates in northeastern Algeria and crosses Tunisia west to east, discharging near the city of Ghar El Melh. The basin covers approximately 23,000 km², with elevations ranging from over 1,200 m in the upstream highlands to less than 50 m above sea level in the downstream floodplain. Land use is dominated by agriculture, accounting for more than 70% of total land cover, with main crops including cereals (wheat and barley), olives, citrus fruits, and vegetables. The basin experiences a semi-arid Mediterranean climate with average annual rainfall ranging from 600 mm in the northwest to about 350 mm in the lower reaches, while potential evapotranspiration exceeds 1,200 mm yr⁻¹ (DGRE 2019; Sawassi et al. 2024).

From a WEF nexus perspective, the basin illustrates classic intersectoral trade-offs: irrigation withdrawals compete with urban supply during dry years; domestic water transfers from the Medjerda sustain over one-third of Tunisia's population; and altered flow regimes reduce natural recharge and ecological connectivity downstream. Over-abstraction of groundwater has led to declining piezometric levels and increasing salinisation in downstream irrigation zones.

An existing WEAP model developed for the Lower Medjerda and Sloughia-Mjez systems under earlier national water planning initiatives (DGRE 2019) was adapted for WatNEX compatibility. The original model was a detailed operational tool that lacked explicit domestic demand nodes for basin residents and focused heavily on inter-basin transfers. For WatNEX integration, the model was simplified and standardised, as shown in Each sub-basin was aggregated into a single catchment node internally divided into nature, rainfed agriculture, irrigated agriculture, and other uses. Domestic and industrial demand nodes were separated from previously combined nodes, and reservoirs and groundwater nodes were retained only where they directly contributed to system regulation. Two regions were identified, the main Medjerda sub-region and the Sloughia sub-region.

Based on the existing challenges in the basin, the following two scenarios were built to analyze nexus synergies and trade-offs:

- Since the Lower Medjerda River Basin plays a vital role in supporting both agricultural production and urban development in northern Tunisia, the first scenario (S1) considers a land-use conversion of 20% within the basin, with 10.% of natural area converted to irrigated

agriculture and 10% to urban land use. This represents planned irrigation expansion and continuing urban growth trends in the Greater Tunis and Cap Bon regions

The second scenario (S2) builds upon the pressures identified in the first scenario and investigates the potential role of desalination in alleviating water shortages and improving supply reliability for urban and industrial users. The scenario assumes an additional supply of 50,000 m³ per day through desalinated water into the urban supply network, reducing dependency on freshwater transfers.

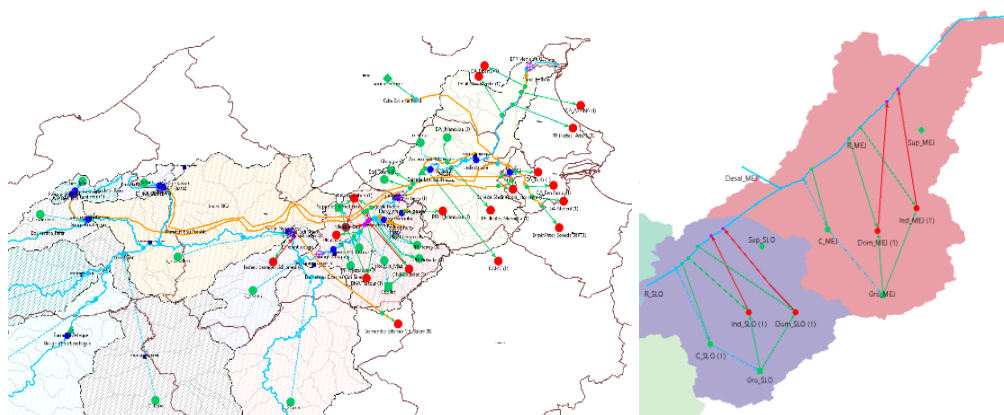


Figure 3. (Left) WEAP model developed by the Government of Tunisia, (Right) Simplified WEAP model in line with WatNEX requirements.

RESULTS AND DISCUSSION

3.1 Case Study: Tuul River Basin (Mongolia)

The WatNEX demand-supply analysis (Figure 4) reveals that domestic demands are highest, followed by industrial and irrigated agriculture. Significant shortages are observed across all three sectors: 49% in domestic, 59% in irrigation, and 48% in industrial. These shortages arise because surface water supply alone is insufficient; in practice, they are partially offset by increasing (informal) groundwater use.

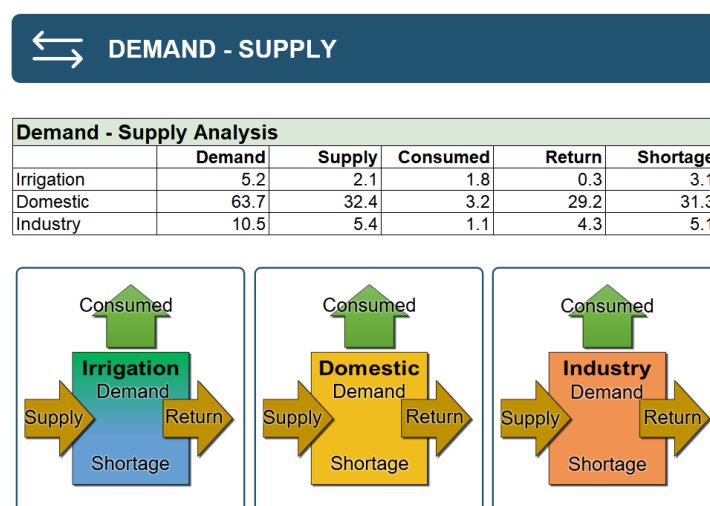


Figure 4. Sectoral supply-demand gap for the Tuul River Basin under baseline conditions, as shown in WatNEX.

The Green Water Balance confirms that evapotranspiration from natural areas dominates the green water flux, while irrigated and rainfed areas contribute comparatively little, reflecting their small spatial extent. The Blue Water Balance shows that return flows from the domestic sector (29.2 MCM) contribute more significantly to downstream water availability than those from industry (4.3 MCM), which has a higher consumptive fraction.



Water Accounting Engine to support NEXUS analysis

powered by FutureWater

INSTRUCTIONS

IMPORT

WATER ACCOUNTS

NEXUS BALANCES

SCENARIO ANALYSIS

Sector	Variable	00_Reference	01_PopulationGr	02_CC	03_GW_pumping
WATER m3	Precipitation	14,070,150,129	0.0%	1.6%	0.0%
	Evapotranspiration	13,564,575,146	0.0%	1.4%	0.0%
	Demand	79,411,519	161.4%	0.0%	0.0%
	Unmet demand	39,518,023	197.9%	-2.5%	-36.2%
	Runoff	497,366,693	0.0%	6.8%	0.0%
ENERGY kWh	Import	0	0.0%	0.0%	0.0%
	Production	3,182,589,600	0.0%	0.0%	0.0%
	Available	3,182,589,600	0.0%	0.0%	0.0%
	Demand	24,539,168,479	7.5%	0.0%	261.2%
	Consumption	3,182,589,600	0.0%	0.0%	0.0%
	Shortage	21,356,578,879	8.6%	0.0%	300.2%
	Export	0	0.0%	0.0%	0.0%
FOOD ton	Import	0	0.0%	0.0%	0.0%
	Production	8,387	0.0%	0.6%	10.3%
	Available	8,387	0.0%	0.6%	10.3%
	Demand	3,652	0.0%	0.0%	0.0%
	Consumption	3,652	0.0%	0.0%	0.0%
	Shortage	0	0.0%	0.0%	0.0%
	Export	4,735	0.0%	1.1%	18.3%
ECOSYSTEM mUS\$	Production	56	-1.0%	5.4%	1.8%
	Consumption	1,595	7.5%	0.0%	261.2%

Figure 5. Synergies and trade-offs observed across the four nexus domains for the modelled population growth, increased precipitation (under climate change) and groundwater pumping scenarios in the Tuul River Basin, as shown in WatNEX.

In Figure 5, the names given to the scenarios within WEAP. 01_PopulationGrowth (Scenario 1), 02_CC (Climate Change - Scenario 2), and 03_GW_pumping (Scenario 3). The nexus balances and scenario results (

Figure 5) quantify the impacts across all four WEF sectors. Under the population growth scenario (1.5% annual increase in Ulaanbaatar population), water demand would increase by 161% on average (2020-2030), generating an overall average shortage of 117 MCM. Of this, Region 4 (Ulaanbaatar) alone accounts for 97 MCM of this shortage (not shown in the table, user needs to select the region of interest in the model dialogue to see individual regional values) . Higher sectoral water consumption reduces overall outflows, which in turn results in a modest negative ecosystem impact (~1%). [The 161% is the increase in water demands (figure 5) under the population growth of 1.5% scenario and possible 117 MCM water shortage. This scenario leads to 197.9% increase in unmet demands, a significant increase from 39,518,023 m³ of the baseline (zero population increase)]

Under the climate change scenario (SSP2-4.5, 2020-2039), a projected 2% increase in precipitation reduces unmet water demands by 2.5%, improves food production by 0.6% due to greater water

availability (thus reducing the demand-supply gap as a result of higher precipitation within the basin) which also results in more water available for irrigation and food production, as well as increases ecosystem production by 5.4% as a result of higher outflows.

The groundwater abstraction scenario produces the sharpest cross-sectoral trade-offs. Unmet domestic demand falls by 36%, and greater water availability supports a 10% increase in food production and an 18% increase in food export. However, these gains come at a cost of a 261% increase in energy demand resulting from additional groundwater pumping, which in turn increases energy shortages by 300% and intensifies ecosystem impacts through elevated CO₂ emissions from fossil fuel-based energy production. Although ecosystem production increases by 1.8% due to greater water availability, ecosystem consumption rises by 261% driven by the energy penalty. This trade-off would be invisible to a water-only analysis.

3.2 Case Study: Lower Medjerda Basin (Tunisia)

Baseline water accounts (2010-2020 average) show that upstream inflow is the primary contributor to water availability in the basin, followed by local precipitation runoff (958 MCM/yr). Evapotranspiration accounts for approximately 40% of total water outputs. Groundwater is used sustainably, with an average net annual recharge of 75 MCM.

The demand-supply analysis reveals that households are the largest water user (677.2 MCM/yr supplied), followed by irrigation (107 MCM of blue water supply plus 109.4 MCM from direct precipitation) and industry (27.1 MCM). A shortage of 24.8 MCM/yr (19% of total irrigation demand) persists on an annual basis. The domestic sector faces an even larger absolute shortage of 86.4 MCM/yr, representing an 11% deficit relative to total domestic demand.

Expressed as percentage change relative to the baseline, the results (Figure 6) for the land-use change scenario (S1) show that overall water demand increases by 0.3% and water shortage by 1.6%, while evapotranspiration rises by only 0.1%, indicating that the available water resources have limited capacity to absorb additional demand. The 10% expansion of irrigated area yields only a ~1% increase in food production, well below what area expansion alone would suggest, as a direct consequence of pre-existing water scarcity. Ecosystem values are reduced by nearly 0.03% due to the conversion of natural areas.

The desalination scenario (S2) reduces unmet water demand by 6.2% and increases food production by 1.6% compared to baseline, also reducing food shortage by 0.7%. However, the energy penalty is substantial as the energy demand rises by 2.9% and energy consumption by 5.7%, leading to a 3.7% reduction in energy export (Figure 6). Ecosystem production increases modestly (+0.4%) due to higher outflows, but ecosystem consumption also rises (+2.9%), driven by increased energy use.

3.3 Cross-case synthesis

Together, the two demonstration cases illustrate how WatNEX provides a consistent analytical framework for diagnosing WEFE nexus dynamics across varying basin contexts.

Trade-off visibility: Both case studies expose cross-sectoral interactions that single-sector analyses would miss. In Mongolia, a 36% reduction in unmet water demand through groundwater abstraction triggers a 261% rise in energy demand. In Tunisia, desalination achieves a more modest 6% reduction in unmet demand but still incurs a 5.7% increase in energy consumption. The contrast in magnitude illustrates that the energy cost of additional water supply is context-dependent, shaped by the energy source (fossil-based pumping in Mongolia versus grid-connected desalination in Tunisia). WatNEX makes these interactions explicit and quantifiable, reinforcing the case that WEFE decision-making requires tools that systematically account for interlinkages (Albrecht et al. 2018).



Water Accounting Engine to support NEXUS analysis

powered by FutureWater

INSTRUCTIONS

IMPORT

WATER ACCOUNTS

NEXUS BALANCES

SCENARIO ANALYSIS

Sector	Variable	Reference	LU-Change_20%	Desalination
WATER MCM	Precipitation	958	0.0%	0.0%
	Evapotranspiration	830	0.1%	0.3%
	Demand	926	0.3%	0.3%
	Unmet demand	115	1.6%	-6.2%
	Runoff	141	0.1%	0.1%
ENERGY GWh	Import	2,196	0.0%	0.0%
	Production	44	0.0%	0.0%
	Available	2,240	0.0%	0.0%
	Demand	1,714	0.0%	2.9%
	Consumption	879	0.0%	5.7%
	Shortage	835	0.0%	0.0%
	Export	1,361	0.0%	-3.7%
FOOD ton	Import	29,280	0.0%	0.0%
	Production	230,702	1.1%	1.6%
	Available	259,982	1.0%	1.4%
	Demand	807,274	0.0%	0.0%
	Consumption	259,982	1.0%	1.4%
	Shortage	547,292	-0.5%	-0.7%
	Export	0	0.0%	0.0%
ECOSYSTEM mUS\$	Production	59	0.0%	0.4%
	Consumption	56	0.0%	2.9%

Figure 6. Synergies and trade-offs observed across the four nexus domains for the modelled land use change and desalination scenarios in the Lower Medjerda Basin, as shown in WatNEX.

Asymmetry between area expansion and production gains: In both basins, water availability is the binding constraint on food production. In Tunisia, a 10% irrigated area expansion yields only a 1% food production increase. In Mongolia, use of groundwater produces a larger food gain (10%) but the accompanying 261% energy penalty limits its practical value.

Applicability and data accessibility: Mongolia demonstrated WatNEX with a new WEAP setup in a data-scarce basin while Tunisia demonstrated adaptation of an existing operational model. Both pathways integrated successfully, confirming the tool's flexibility. The reliance on globally available datasets, such as CHIRPS (Funk et al. 2015), Dynamic World Land Cover (Brown et al. 2022), LGRIP (Teluguntla et al. 2023), ERA5-Land (Muñoz-Sabater et al. 2021), GPWv4 (CIESIN 2018) and FAO-56 (Allen et al. 1998), makes WatNEX accessible in data-scarce environments where integrated tools are most needed (Purwanto et al. 2021; Shannak et al. 2018). Compared with existing nexus frameworks such as CLEWS (Howells et al. 2013) and WEF Nexus Tool 2.0 (Daher & Mohtar 2015), WatNEX focuses on water accounting as the entry point, using WEAP to generate spatially resolved water balances that are translated into energy, food, and ecosystem indicators through conversion factors embedded in the plugin.

3. CONCLUSIONS

This paper demonstrated WatNEX as an operational WEF nexus assessment tool that provides a consistent, reproducible framework applicable across contrasting modelling conditions and data environments. Key findings include: (i) baseline water shortages of 48-59% across all demand sectors in the Tuul River Basin; (ii) irrigation expansion in the Lower Medjerda Basin constrained by water

availability rather than land, yielding only 1% food gains from 10% area expansion; (iii) non-conventional supply strategies (groundwater pumping, desalination) that offer water security benefits but introduce energy and ecosystem costs.

Beyond these interventions, the projection scenarios underline that external drivers shape nexus outcomes as strongly as management choices. In the Tuul River Basin, the SSP2-4.5 climate scenario, with a projected 2% precipitation increase, reduced unmet water demand by 2.5% and improved food and ecosystem production, whereas population growth in Ulaanbaatar widened the supply-demand gap by 117 MCM. Together with the supply-side interventions, these results show that no single sector can be optimised in isolation without shifting pressure onto another.

The central implication for decision-makers is that water-security gains from groundwater abstraction or desalination must be weighed against their energy and ecosystem penalties, which WatNEX makes explicit and quantifiable. By translating water accounting outputs into integrated WEFE indicators within an accessible WEAP-and-Excel workflow, the tool supports transparent trade-off analysis in both data-scarce and data-rich basins. Future work should extend the demonstration to additional basins and sectors, refine the algorithms that link water balances to energy, food, and ecosystem outcomes, and couple WatNEX with participatory planning processes so that the trade-offs it reveals can inform cross-sectoral policy and investment decisions.

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A SPATIAL TARGETING FRAMEWORK FOR REDUCING WATER-ENERGY-FOOD ACCESS INEQUALITIES IN MALAWI

Faith Mbonongo Banda¹, Chisomo Mkwandah², Joyce Nyuma Chivunga³,
Paul Rowley¹, Richard Blanchard¹

ABSTRACT

A systems understanding of the interrelationships between water, energy, and food through the Water–Energy–Food (WEF) nexus can support strategies for reducing inequalities in resource access. This study developed a Spatial Targeting Framework to identify and address district-level WEF vulnerabilities in Malawi using data from the Integrated Household Survey (IHS5) 2019–2020. Results show near-universal energy poverty (98.8%), high food stress (74.4%), and a mean composite WEF stress index score of 1.92. Spatial analysis reveals strong correlation of food stress and combined WEF vulnerability, particularly in the Southern Region. The Spatial Autoregressive (SAR) model, which accounts for spatial dependence among neighbouring districts, further indicates notable spatial knock-on effect / spillovers ($\rho = 0.2580$), implying that improvements in WEF access in one district tend to be associated with improvements in neighbouring districts. The proposed Spatial Targeting Framework classifies districts into High, Medium, and Low-Priority levels based on combined water-energy-food stress. High-priority districts, concentrated in the Southern Region, require integrated WEF intervention hubs, while medium and low-priority areas need targeted and routine interventions, respectively. The study contributes to the operationalization of the WEF nexus by providing a practical and spatially informed framework that can reduce inequalities in integrated resource access. The findings offer actionable insights for policymakers seeking to design equitable and coordinated WEF interventions in Malawi and similar African settings.

Keywords: Water-Energy-Food nexus, spatial WEF Index Analysis, WEF Nexus Framework, Malawi

1. INTRODUCTION

Water scarcity is increasingly constraining energy production and food systems, yet these sectors are often studied and managed in isolation despite their strong interdependencies (Lu et al., 2026; Zhang et al., 2018). The Water–Energy–Food (WEF) nexus has emerged as a key framework for understanding the interactions, synergies, and trade-offs among these sectors amid climate change, population growth, urbanisation, and environmental degradation (Hoff, 2011; Mabhaudhi et al., 2019). In Africa, where inequalities in access to water, energy, and food remain widespread, the WEF nexus offers a pathway toward integrated and sustainable development (Botai et al., 2021; African Development Bank, 2025). However, planning approaches in many countries continue to rely on fragmented, sector-driven strategies, resulting in inefficient resource allocation and overlooked trade-offs (Lu et al., 2026; Ningi & Mullen, 2025).

These challenges are particularly evident in Malawi, which faces severe energy poverty. According to the Fifth Integrated Household Survey (IHS5), 98.8% of households rely on solid biomass fuels, primarily firewood and charcoal, for cooking (NSO, 2020; Mwale et al., 2026), alongside high levels of food stress (74.4% from own analysis of IHS5 data) (NSO, 2020) and persistent water access gaps. These vulnerabilities are unevenly distributed across districts, with the Southern Region being particularly

¹ Centre for Renewable Energy Systems Technology, Loughborough University, Epinal Way, Loughborough LE11 3TU, United Kingdom

² Malaria Epidemiology Research Group, Malawi Liverpool Wellcome Research Programme, P.O. Box 30096, Chichiri, Blantyre Malawi.

³ Department of Energy Resources Management, Malawi University of Science and Technology, Limbe P.O. Box 5196, Malawi.

affected. Although policy interest in the WEF nexus has increased, implementation remains limited and inadequately addresses regional inequalities and inter-district spillover effects, whereby vulnerabilities or resource constraints in one district influence conditions in neighbouring districts through shared environmental systems, markets, infrastructure, and socio-economic linkages (Bhave et al., 2022; John et al., 2023; Li et al., 2021). Furthermore, WEF interactions vary across local socioeconomic and environmental contexts, highlighting the need for integrated and spatially informed modelling approaches to support evidence-based decision-making (Kemp et al., 2021). This study develops a spatial targeting framework that could reduce inequalities in integrated Water–Energy–Food access in Malawi.

The specific objectives of the study were to:

1. Quantify and map district-level inequalities in integrated Water–Energy–Food access across Malawi using IHS5 and GIS techniques.
2. Identify spatial clustering, dependence, and spillover effects of WEF vulnerabilities using spatial econometrics models; and
3. Demonstrate the application of the proposed spatial targeting framework using Chiradzulu District as a case study

2. METHODOLOGY

2.1 Study Area

Malawi, as shown in Figure 1, offers a compelling case for studying the Water–Energy–Food (WEF) nexus in sub-Saharan Africa due to its acute and interconnected challenges in water, energy, and food security, coupled with pronounced spatial inequalities. Administratively, Malawi is divided into 28 districts across three regions: Northern, Central, and Southern. Agriculture remains the backbone of the economy and plays a central role in livelihoods and food systems (Brewster, 2025). Chiradzulu District was selected as the case study district because it emerged as a high-priority area for targeted WEF interventions. The country exhibits substantial geographic and socioeconomic heterogeneity. The Southern Region is relatively more densely populated and experiences higher levels of food insecurity and environmental pressure, while the Northern Region is comparatively less vulnerable but characterised by greater remoteness and infrastructure limitations.

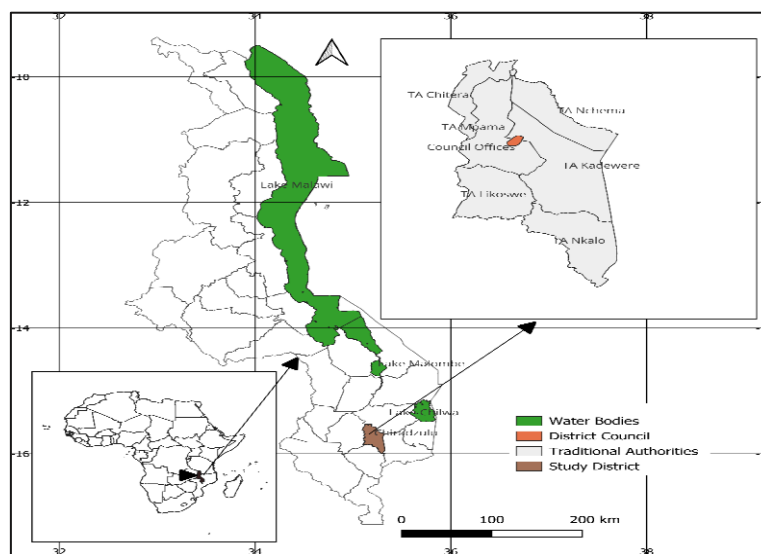


Figure 1. Map of the study area

2.2 Data Sources

This study used data from the Fifth Integrated Household Survey (IHS5) conducted by the Malawi National Statistical Office in 2019–2020 (NSO, 2020). The IHS5 is a nationally representative survey covering 11,434 households and provides detailed information on water access, energy use, food security, and household welfare. Sampling weights were applied in all analyses to ensure that the survey results accurately represent the national population. These weights adjust for differences in households' probabilities of selection and account for non-response arising from the survey's complex stratified two-stage cluster sampling design. The survey employed district-level stratification, with enumeration areas selected using probability proportional to size and households randomly sampled within each enumeration area. Household-level indicators were subsequently aggregated to the district level for spatial analysis. In addition, the case study analysis for Chiradzulu District utilized district-level data collected in 2015.

2.3 Theoretical Framework

The study was grounded in the Water–Energy–Food (WEF) Nexus Framework, which recognises the interdependence between water, energy, and food systems (Hoff, 2011; Mabhaudhi et al., 2019). Spatial Dependence Theory was also incorporated to account for geographic clustering and spillover effects between neighbouring districts (Anselin, 1988).

2.4 Construction of the Water–Energy–Food Vulnerability Index

Three dimensions of WEF vulnerability were constructed at the household level: water stress, energy poverty, and food stress.

A household was classified as experiencing water stress if it spent more than 30 minutes collecting water (including walking and waiting time) or relied on a seasonal water source:

$$W_i = \begin{cases} 1, & \text{if } T_i > 30 \text{ or } S_i = 1 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where T_i is the total time spent collecting water and S_i indicates reliance on a seasonal water source. A household was classified as experiencing energy poverty if it lacked electricity access or relied on non-modern cooking fuels:

$$E_i = \begin{cases} 1, & \text{if no electricity access or no modern cooking fuel} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

household was classified as experiencing food stress if it reported food shortages or reduced meal frequency:

$$F_i = \begin{cases} 1, & \text{if food shortage or reduced meal frequency is reported} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Each indicator was coded as a binary variable (1 = vulnerable; 0 = not vulnerable).

A composite Water–Energy–Food (WEF) stress index was then constructed as the sum of these three binary indicators (OECD & JRC, 2008; Nardo et al., 2005)

$$WEF_i = \sum_{j=1}^3 D_{ij} \quad (4)$$

where D_{ij} represents the vulnerability status of household i in dimension j (water, energy, or food), taking a value of 1 if the household is vulnerable and 0 otherwise.

$$D_{ij} \in \{0,1\}$$

To facilitate spatial analysis, household-level WEF vulnerability scores were aggregated to the district level using survey sampling weights (United Nations, 2005):

$$WEF_d = \frac{\sum_{i=1}^{n_d} w_i (W_i + E_i + F_i)}{\sum_{i=1}^{n_d} w_i} \quad (5)$$

where WEF_d denotes the district-level WEF vulnerability index for district d , w_i is the sampling weight of household i , and n_d is the total number of sampled households in district d .

2.5 Spatial and Econometric Analysis

Spatial dependence was assessed using a Queen contiguity spatial weights matrix, in which districts sharing a common boundary or vertex were considered neighbors. Global Moran's I was used to assess the overall degree of spatial autocorrelation, while Local Indicators of Spatial Association (LISA) were used to identify statistically significant hotspots, cold spots, and spatial outliers.

To examine the determinants of district-level WEF vulnerability, Ordinary Least Squares (OLS), Spatial Autoregressive (SAR), and Spatial Error Models (SEM) were estimated. The OLS model was specified as:

$$Y_i = \beta_0 + \beta_1 HW_i + \beta_2 HF_i + \beta_3 HE_i + \varepsilon_i \quad (6)$$

Y_i denotes the district-level WEF vulnerability index; HW_i , HF_i , and HE_i denote the district-level weighted proportions of households experiencing water stress, food stress, and energy poverty, respectively, derived from IHS5 household survey data. For example, a value of $HW_i = 0.25$ indicates that 25% of weighted households in district i experienced water stress. The Spatial Autoregressive (SAR) model was specified as:

$$Y = \rho WY + X\beta + \varepsilon \quad (7)$$

where W is the Queen contiguity spatial weights matrix, ρ is the spatial autoregressive coefficient measuring spillover effects between neighboring districts, X is the matrix of explanatory variables (HW , HF , and HE), and β is the vector of model coefficients. The Spatial Error Model (SEM) was specified as:

$$Y = X\beta + u \quad (8)$$

Whereby: $u = \lambda Wu + \varepsilon$

where u is the spatially correlated error component, λ measures spatial dependence in the error term, and the remaining parameters are defined as above.

Table 1 presents the variables used in the spatial regression analysis. The dependent variable is the district-level Water–Energy–Food (WEF) vulnerability index, while the explanatory variables comprise the weighted proportions of households experiencing water stress, food stress, and energy poverty. The table also defines the spatial parameters and the Queen contiguity spatial weights matrix employed in the Spatial Autoregressive (SAR) and Spatial Error Models (SEM).

Table 1. Variables Used in the Spatial Regression Models

Variable	Description
Y	District-level WEF vulnerability index
HW	Weighted proportion of households experiencing water stress
HF	Weighted proportion of households experiencing food stress
HE	Weighted proportion of households experiencing energy poverty
W	Queen contiguity spatial weights matrix
ρ	Spatial autoregressive coefficient (SAR model)
λ	Spatial error coefficient (SEM model)

Model selection was based on Lagrange Multiplier diagnostics and Akaike Information Criterion (AIC), with lower AIC values indicating better model fit (Azzam et al., 2023; Taguta et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Descriptive Statistics of WEF Vulnerabilities

National descriptive statistics indicate that energy poverty affects 98.8% of households, followed by food stress (74.4%) and water stress (19.1%) (NSO, 2020). The composite Water–Energy–Food (WEF) stress index score was calculated as the sum of three binary indicators representing water stress, energy poverty, and food stress, resulting in household scores ranging from 0 to 3, where higher values indicate greater multidimensional vulnerability. The mean weighted WEF stress index score was 1.92, obtained by averaging household-level index scores across the sample. Households were classified as experiencing no stress (score = 0), moderate stress (score = 1), high stress (score = 2), and critical stress (score = 3). Based on this classification, 63.4% of households experienced high stress and 15.0% experienced critical stress as shown in Figure 2.

A mean WEF score of 1.92 indicates substantial multidimensional deprivation. These findings suggest that multidimensional deprivation in Malawi is driven primarily by energy and food insecurity, consistent with evidence from Southern Africa linking WEF inequalities to poverty, infrastructure deficits, and climate-sensitive livelihoods.

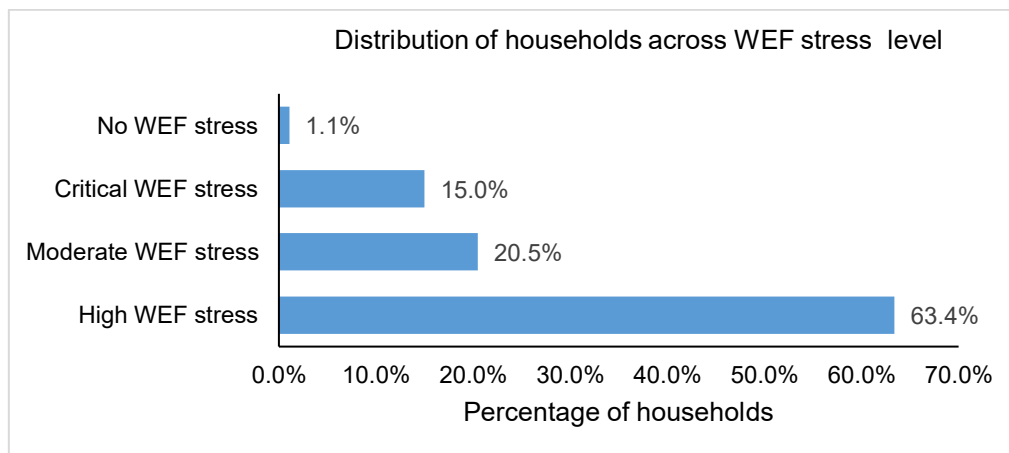


Figure 2. Distribution of households across WEF stress level

Furthermore, Figure 3 shows substantial regional variation in WEF vulnerability across Malawi. The Southern Region recorded the highest food stress and overall WEF stress composite scores, while the Northern Region showed relatively lower vulnerability. Water stress remained relatively similar across regions, suggesting that overall WEF inequalities are mainly driven by food and energy deprivation (Bhave et al., 2022; Li et al., 2021). These findings highlight the need for region-specific interventions and more targeted resource allocation within national WEF strategies (African Development Bank, 2025; Mabhaudhi et al., 2023).

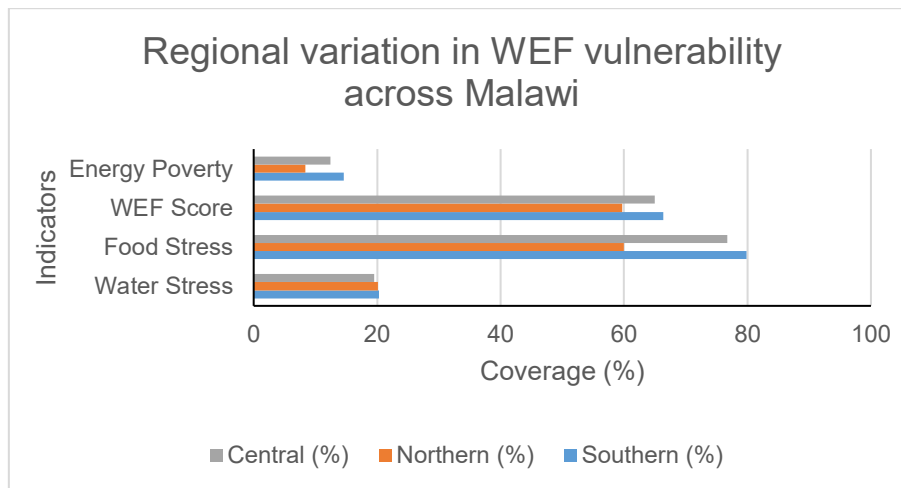


Figure 3. Regional distribution of Water–Energy–Food (WEF) vulnerability indicators

3.2 Spatial Dependence and Diagnostic Tests

Figure 4 illustrates the spatial distribution of water stress, food stress, and energy poverty across Malawi. Food stress exhibits clear geographic clustering, particularly in the Southern Region, likely reflecting the combined effects of climatic shocks, high population density, land fragmentation, and reliance on rain-fed agriculture. In contrast, energy poverty shows little spatial variation due to its near-universal prevalence across districts. These findings suggest that while food insecurity is spatially concentrated, energy deprivation remains a nationwide structural challenge.

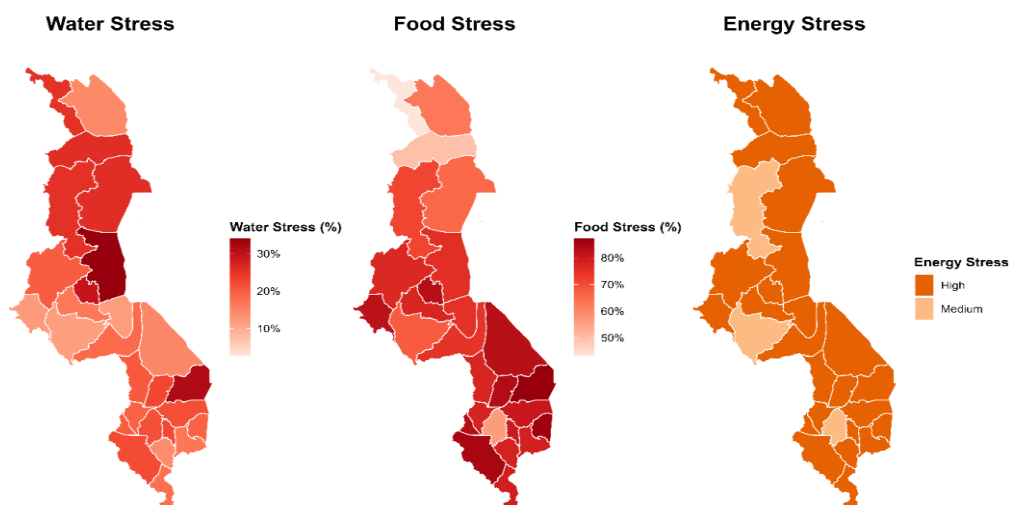


Figure 4. Spatial Distribution of Water, Food, and Energy Vulnerabilities Across Districts

Spatial analysis revealed spatial correlation between food stress and combined WEF vulnerability across Malawi. Global Moran's I statistics revealed significant positive spatial autocorrelation for food stress ($I = 0.4945$, $p < 0.01$) and combined WEF stress ($I = 0.3202$, $p < 0.05$), across districts, whereby districts with similar levels of vulnerability tend to be located near one another (Table 2). Robust Lagrange Multiplier diagnostics supported the use of spatial lag specification, a model that accounts for the influence of conditions in neighbouring districts on outcomes within a district. Consequently, spatial econometric models were estimated, with the Spatial Autoregressive (SAR) model selected as the preferred specification.

Table 2. Spatial Dependence and Lagrange Multiplier Diagnostics

Indicator/Test	Moran's I Statistic	<i>P</i>
Water Stress	0.1350	0.0871
Food Stress	0.4945	0.0000***
Energy Poverty	-0.0087	0.3902
Combined WEF Stress	0.3202	0.0030**

Note: Significance levels are denoted as *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$

As shown in Table 3, the SAR model provided the best fit, with the lowest Akaike Information Criterion (AIC), where lower values indicate a better-fitting model, and the highest log-likelihood, where higher values indicate improved model performance. The positive spatial autoregressive coefficient ($\rho = 0.2580$) indicates the presence of spatial spillover effects, meaning that higher WEF vulnerability in one district is associated with higher vulnerability in neighboring districts.

Table 3. Spatial Regression Model Comparison

Variable	OLS	SAR	SEM
Intercept	0.4048***	0.2959	0.4035
Water Stress	0.0415**	0.0353	0.0387
Food Stress	0.0646***	0.0445	0.0681
Energy Poverty	0.0296	0.0385	0.0186
Spatial Rho (ρ)	–	0.2580	–
Spatial Lambda (λ)	–	–	0.4911
Log-likelihood	47.8	52.2	50.2
AIC	-85.6	-92.5	-88.3

Note: ρ (Spatial Rho) measures spatial dependence between neighbouring districts in the SAR model, while λ (Spatial Lambda) measures spatial dependence in the error term in the SEM model. Higher log-likelihood values and lower AIC values indicate better model fit. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

This finding implies that resource deprivation can spread through interconnected agricultural markets, migration, shared water systems, and regional climatic conditions. The presence of spatial spillover effects suggests that interventions implemented in one district may influence outcomes in neighboring districts because the spillover effects likely arise because neighbouring districts share transboundary water resources, climatic conditions, agricultural systems, markets, transport corridors, and in some cases energy infrastructure. Consequently, improvements or vulnerabilities in one district may influence neighbouring districts, making coordinated regional approaches potentially more effective than isolated district-level interventions. Building on the vulnerability maps and our spatial econometric findings, and consistent with previous WEF nexus studies (Bhave et al., 2022; John et al., 2023; Mabhaudhi et al., 2023), the study proposes a Spatial Targeting Framework to prioritize WEF interventions across Malawi.

3.3 Spatial Targeting Framework

The Spatial Targeting Framework was developed by combining spatial results with district-level WEF vulnerability patterns. Based on percentile rankings of the composite WEF stress index, districts were classified into three intervention priority levels: High, Medium, and Low. As shown in Figure 5, high-priority districts are predominantly concentrated in the Southern Region, highlighting substantial geographic inequalities in WEF vulnerability. Finally, the framework links each priority category to tailored policy response pathways (Table 4). High-priority districts require integrated WEF intervention hubs and infrastructure investments, medium-priority districts need targeted resilience-building programs, and low-priority districts focus on routine monitoring and maintenance interventions. This spatially informed approach aligns with WEF nexus implementation strategies recommended for Southern Africa (Mabhaudhi et al., 2023; Taguta et al., 2023; Bhave et al., 2022).

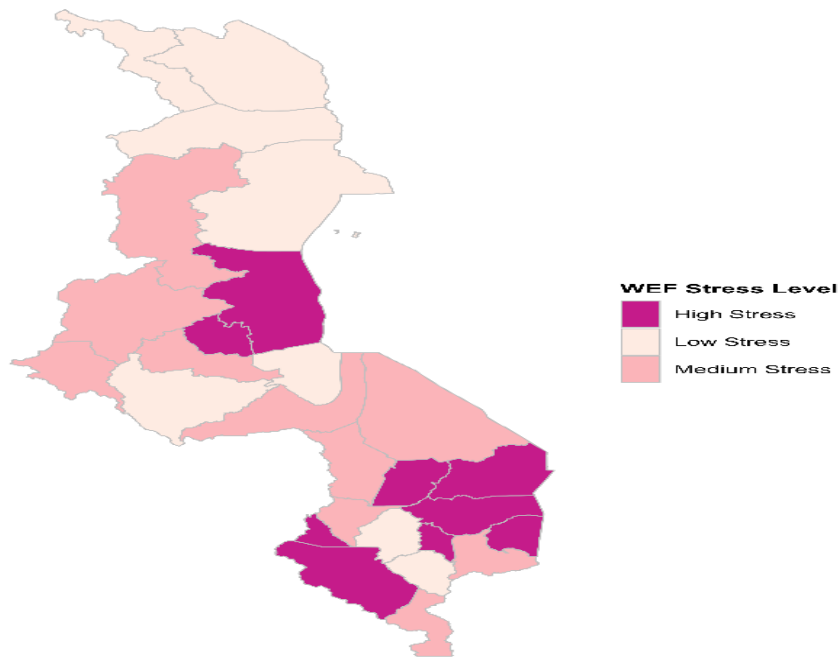


Figure 5. District priority levels based on combined Water-Energy and Food stress

Table 4. WEF recommended interventions

Priority Level	Characteristics	Recommended Intervention
High	Severe food-water stress concentration	Integrated WEF hubs, irrigation, solar mini grids
Medium	Moderate vulnerability	Targeted subsidies, resilience programmes
Low	Relatively stable districts	Monitoring and maintenance

3.4 Practical Application of the Spatial Targeting Framework: Chiradzulu Case Study

To contextualize the Spatial Targeting Framework, secondary evidence from a household water and energy needs assessment conducted in Chiradzulu District was incorporated (Phiri et al., 2020). Chiradzulu was selected because it represents a high-priority WEF vulnerability area identified in the national spatial analysis.

As shown in Figure 6, the assessment revealed substantial water access challenges: 63% of households spent more than 30 minutes collecting water, while 79% did not treat drinking water before consumption. Although most households relied on boreholes, these findings highlight persistent constraints in water access, quality, and safety. They also demonstrate how water insecurity intersects with broader WEF vulnerabilities, particularly by reducing opportunities for agricultural production, education, and income-generating activities. (Li et al., 2021; Bhawe et al., 2022).

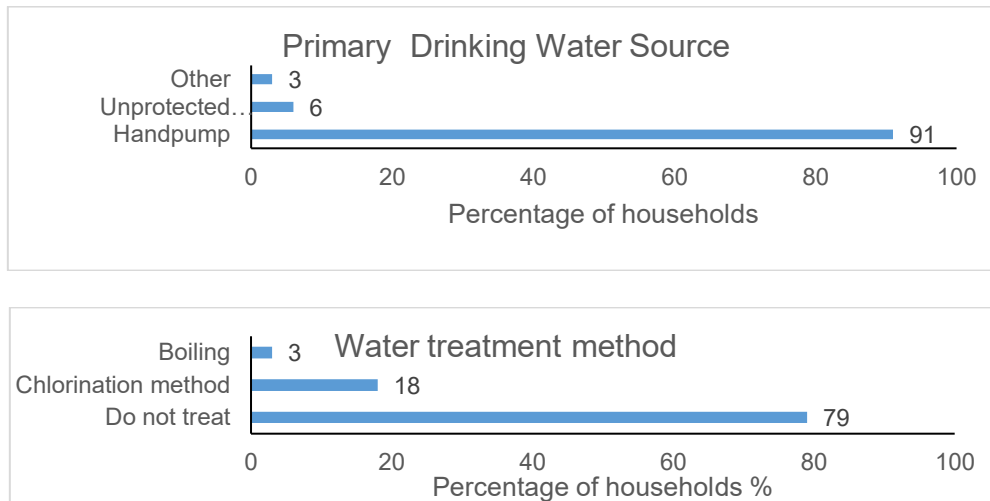


Figure 6. Household Drinking Water Sources and Water Treatment Methods in Chiradzulu

Figure 7 indicates that battery-powered LED torches were the primary source of lighting, while firewood was the dominant cooking fuel in Chiradzulu District as shown in Figure 8. These patterns reflect pervasive energy poverty and limited access to modern energy services, consistent with previous evidence from rural Malawi and Southern Africa (Mabhaudhi et al., 2019; Bhawe et al., 2022). Combined with the water access constraints identified in the district, the findings highlight the interconnected nature of WEF deprivation, where inadequate energy access restricts water supply, irrigation, food preservation, and livelihood opportunities (Li et al., 2021; John et al., 2023).

The Chiradzulu case study further demonstrates the practical relevance of the proposed Spatial Targeting Framework by linking district-level vulnerability patterns to household-level experiences. The findings suggest that integrated interventions, such as solar-powered WEF hubs, could simultaneously improve water access, irrigation, household energy supply, food processing, and income-generating activities, thereby addressing multiple dimensions of deprivation in high-priority districts (Mabhaudhi et al., 2023; Taguta et al., 2023).

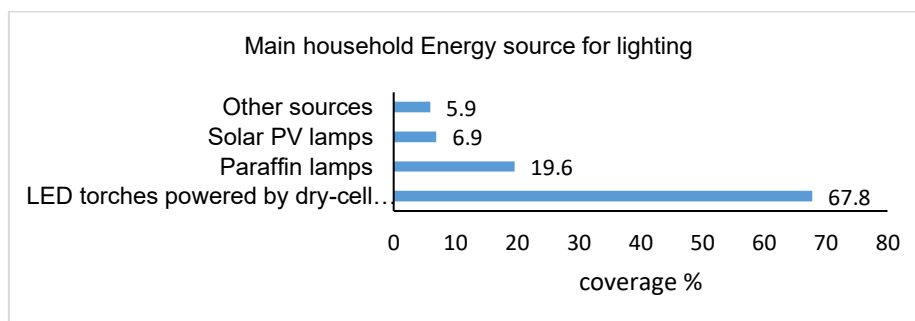


Figure 7. Main household Energy source for lighting

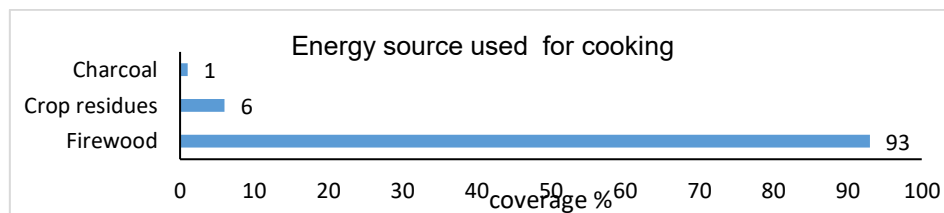


Figure 8. Energy source used for cooking

4. CONCLUSION

This study developed a spatial targeting approach to address the variation in Water–Energy–Food (WEF) index in Malawi using district-level data from the 2019–2020 Integrated Household Survey. The findings reveal widespread WEF vulnerabilities, with significant correlation of food stress and combined WEF stress in the Southern Region. Spatial analysis further identified inter-district spillover/ knock-on effects ($p = 0.2580$), indicating that WEF vulnerability in one district is positively associated with vulnerability in neighboring districts. This suggests that WEF challenges are geographically interconnected rather than randomly distributed, particularly in areas exhibiting correlation of high food stress and combined WEF vulnerability. Based on these findings, a Spatial Targeting Framework was developed to classify districts into High-, Medium-, and Low-Priority intervention categories. By integrating vulnerability mapping, hotspot analysis, and spatial modelling, the framework provides a practical tool for geographically informed and enhanced WEF planning.

The results highlight the need for coordinated and spatially targeted policy responses. High-priority districts require integrated investments in water infrastructure, clean energy access, climate-resilient agriculture, and food security programs, while medium-priority areas should focus on resilience-building and low-priority districts on monitoring and clean energy expansion. Given the observed spillover effects, whereby WEF vulnerability in one district is associated with vulnerability in neighboring districts, stronger coordination among district councils, government institutions, and development partners will be essential to maximize intervention effectiveness. Attention should also be given to women-headed households and remote rural communities that experience overlapping forms of deprivation.

Although limited using cross-sectional data, this study demonstrates how spatial analysis can operationalize the WEF nexus by translating vulnerability patterns into actionable policy guidance. The proposed framework offers a scalable and replicable approach for improving the effectiveness, coordination, and equity of WEF interventions in Malawi and other resource-constrained settings.

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ON-FARM WATER ENERGY FOOD CARBON-FOOTPRINT ECONOMIC PERFORMANCE NEXUS INDEX FOR ASSESSMENT OF INTEGRATED RESOURCES MANAGEMENT FOR TOMATO FARMING IN JORDAN

Wafaa Abuhammour¹, Essam M. Ahmed², Safaa Aljaafreh³, Abdel Razzak Al Tawaha⁴, and Mohie El Din Omar⁵

ABSTRACT

The relationship between water use, energy consumption, food production and carbon dioxide production represents one of the most sustainability challenges within agricultural context in Jordan. Inefficient irrigation practices increase groundwater abstraction, energy consumption, production costs, and carbon emissions, while also contributing to soil and water salinity which negatively affecting crop productivity and long-term soil quality. Hence, for quantitative diagnosis of farming performance, the paper presented an on-farm water, energy, food, carbon-footprint, and economic performance (WEFCE) nexus index made up of five pillars. The weighting scheme was established through expert consultation and reflected the relative importance of each dimension under Jordanian conditions. Water received the highest weight (30%) because of Jordan's severe water scarcity and the strategic importance of sustainable water management. Food productivity accounted for 25%, followed by energy (20%), economic performance (15%), and carbon footprint (10%). The resulting index ranges from 0 to 1, where values closer to 1 indicate highest levels of sustainability and integrated resource-use efficiency. The analysis is based on field-level data collected from 308 farms distributed across major agro-ecological regions. The results indicate that the overall sustainability performance of tomato farming is moderate. Most WEFCE Nexus Index values are concentrated between 0.30 and 0.60, with a mean value of approximately 0.42, suggesting that although farms achieve a certain degree of resource integration, considerable room for improvement remains. Farms with higher WEFCE scores are generally characterized by more efficient irrigation practices and better overall resource management. The findings demonstrate that achieving higher crop yields alone does not necessarily translate into sustainable agricultural systems. Instead, improving resource-use efficiency through integrated management approaches is essential. The study therefore recommends strengthening precision irrigation technologies, renewable energy solutions, groundwater governance, and salinity management strategies.

Keywords : On-farm Water-Energy-Food-Carbon Footprint-Economic Performance (WEFCE) Nexus; Agricultural Sustainability ; Tomato Farming

1. INTRODUCTION

Jordan is one of the most water-scarce countries in the world, facing increasing pressure on its limited natural resources due to population growth, climate variability, recurrent droughts, and expanding agricultural demands. Agriculture remains a vital sector for food security, rural livelihoods, and socio-economic development; however, it is also the largest consumer of freshwater resources, relying heavily on groundwater abstraction from increasingly stressed aquifers. The resulting decline in groundwater

¹ Researcher, National Agricultural Research Center (NARC), Jordan. Amman, E-mail: abuhammourwafaa@gmail.com

² Water Resources Planner and FAO-WSI Consultant, Ministry of Water Resources and Irrigation, Egypt; E-mail: essamohab62@gmail.com

³ Researcher, National Agricultural Research Center (NARC). Amman, E-mail: safabj@yahoo.com

⁴ Senior Researcher, National Agricultural Research Center (NARC). Amman, E-mail: abdelrazzaqaltawaha@gmail.com

⁵ ICARDA Country Director for Egypt and Associate Scientist at Soil-water-Agronomy Team, the International Center for Agricultural Research in the Dry Areas (ICARDA); E-mail: m.omar@cgiar.org

levels, rising soil and water salinity, and increasing energy requirements for irrigation present major challenges to the long-term sustainability of agricultural production.

Within this context, the Water-Energy-Food-Carbon Footprint-Economy Performance (WEFCE) Nexus has emerged as an important framework for understanding the complex interactions among resource systems and identifying sustainable management strategies. Unlike conventional sectoral approaches that consider water, energy, food, or environmental systems independently, WEFCE Nexus provides an integrated perspective that captures trade-offs and synergies among these interconnected dimensions while explicitly incorporating ecosystem sustainability.

In recent years, the energy sector has been struggling due to highly increased prices and a shortage of diesel supply. Even generating solar energy resource might expose the water to overconsumption and subsequent shortage as the energy resource is abundant and free of cost. Also, overirrigation and diesel pumping, the CO₂ emission is another output that should be considered. Interventions to address the security of one WEFCE parameter can deteriorate other parameters, and the WEFCE dimensions have been considered separately. To achieve the sustainability of the agriculture system in Jordan under these challenging local conditions, an integrated resources management approach should replace the existing individual water and energy resources management approaches. By far, there is no WEFCE nexus tool in Jordan that can assess the farm performance and its specific package of irrigation and agronomic practices, operationalize the nexus approach, and drive transformative actions on the farm level.

There is a great need for Jordan to have an on-farm water, energy, food, and carbon-footprint (WEFCE) nexus index presenting a diagnosis for each farm performance combining the five metrics rather than assessing each unilaterally. The index is needed to address pressing issues related to sustainable agricultural water and energy uses and implications on food production and carbon emissions. The index is needed to identify and upscale the best bundled practices. Hence, the current paper aims to provide practical insights and policy recommendations that contribute to improving resource-use efficiency, strengthening agricultural resilience, and promoting the long-term sustainability of Jordanian agricultural systems. This is achieved through demonstration of the developed on-farm WEFCE nexus index in 308 tomato-based farmer fields representing diverse inputs, agronomic and irrigation practices, soil types, and agro ecological conditions.

Tomato has been selected as one of the country's most economically important and water-intensive use crops, characterized by high irrigation demand, considerable energy consumption for groundwater pumping, intensive fertilizer use, and sensitivity to climate variability. Tomato (*Solanum lycopersicum* L.) is among the most economically significant vegetable crops in Jordan, consistently ranking as the leading vegetable commodity by both production volume and export value. Annual national tomato production fluctuates between approximately 400,000 and 600,000 tons, with the Jordan Valley accounting for the dominant share of output, particularly during the winter and spring growing seasons (MOA, 2020; FAO, 2022). The crop is cultivated across a continuum of production systems ranging from traditional open-field flood and furrow irrigation prevalent among smallholder and medium-scale farmers in the Jordan Valley - to technologically advanced greenhouse and poly tunnel systems employing drip irrigation and fertigation, which have seen progressive adoption in highland areas and among larger commercial operations (Al-Mefleh et al., 2012). This diversity of production systems renders tomato cultivation an analytically representative and practically significant case study for examining water–energy–food–ecosystem nexus dynamics across contrasting resource-use intensities and management regimes.

2. METHODOLOGY

This study employed an integrated Water-Energy-Food-Carbon Footprint-Economy Performance (WEFCE) Nexus index to assess the sustainability of tomato (*Solanum lycopersicum* L.) production systems in Jordan. The analysis was based on primary field-level data collected from 308 tomato farms distributed across the country's major agro-ecological regions (Figure 1), including the Jordan Valley, the northern and central highlands, and the southern arid zones. These regions represent the diversity

of tomato production systems in Jordan, ranging from traditional open-field cultivation to modern greenhouse systems with varying levels of resource-use intensity.

Data were collected through a structured questionnaire developed under the Regional Water Scarcity Initiative (WSI) and implemented by the National Agricultural Research Centre (NARC) in collaboration with the International Center for Agricultural Research in the Dry Areas (ICARDA). The questionnaire was reviewed by experts and pilot-tested before field implementation to ensure technical accuracy and clarity. It captured comprehensive farm-level information related to irrigation water use, energy consumption, tomato productivity, fertilizer and pesticide applications, soil and irrigation water salinity, and farm economic performance.

The analytical framework adopted an extended WEFCE Nexus approach that integrates five principal elements: water, energy, food, ecosystem, and economic performance. The water element evaluates irrigation efficiency and sustainable water use, while the energy element measures direct and indirect energy consumption associated with irrigation pumping and agricultural inputs. The food element reflects crop productivity and yield performance, whereas the ecosystem element considers environmental sustainability through indicators such as salinity and carbon emissions. The economic element assesses farm profitability and cost efficiency. Integrating these elements enables a comprehensive understanding of the interactions, trade-offs, and synergies among resource systems within tomato production.

To quantify sustainability performance, a composite WEFCE Nexus Index was developed by aggregating normalized indicators using a weighted linear approach. The weighting scheme was established through expert consultation and reflected the relative importance of each element under Jordanian conditions. Water received the highest weight (30%) because of Jordan's severe water scarcity and the strategic importance of sustainable water management. Food productivity accounted for 25% of the total score, followed by energy (20%), economic performance (15%), and ecosystem sustainability (10%). The resulting index ranges from 0 to 1, where values closer to 1 indicate higher levels of sustainability and integrated resource-use efficiency. The composite WEFCE Nexus Index was constructed by aggregating normalized dimension scores using a weighted linear combination:

$$\text{WEFCE Index} = \sum_{i=1}^5 w_i P_i \quad (1)$$

Where P_i denotes the normalized performance score for dimension i and w_i represents the corresponding assigned weight. Dimension weights were established through a structured expert consultation process involving agricultural water engineers, irrigation specialists, environmental scientists, agricultural economists, and extension officers with direct field experience in Jordanian tomato production systems.

Water-use efficiency in tomato production was operationalized through a saved water metric, defined as the volumetric difference between the estimated seasonal crop water requirement (6,000 m³/ha) and the actual recorded on-farm irrigation application:

$$\text{Saved Water} = \text{Water Requirement} - \text{Water Consumption} \quad (2)$$

$$\text{Water Pillar} = \text{Saved Water} / \text{Water Requirement} \quad (3)$$

For example, if a farm consumes 4,600 m³/ha, so the saved water is the difference between the estimated seasonal crop water requirement (6,000 m³/ha) and water consumption (4,600 m³/ha) which is 1,400 m³/ha.

Then the water pillar is computed as the ratio between saved water and water requirement (1,400 / 6,000) = 0.233.

Given the dominant role of groundwater pumping in Jordanian tomato irrigation, total farm energy consumption was estimated as:

$$\text{Total Energy} = \text{Direct Energy} + \text{Indirect Energy} \quad (4)$$

$$\text{Energy Pillar} = \text{Saved Energy} / \text{Maximum Energy requirement} \quad (5)$$

Direct energy inputs included diesel fuel and electricity consumed for irrigation pumping and field operations, as well as grid and solar electricity where applicable. These energy sources were converted to Mega Joules per hectare (MJ ha⁻¹) using internationally recognized energy conversion factors (1 L diesel = 38.68 MJ; 1 kWh electricity = 3.60 MJ). The indirect energy consumption was consumed due to manufacturing fertilizers and pesticides and producing seeds outside the farm with specific energy for nitrogen, phosphate, and potassium fertilizers were 66.14, 12.44, and 11 MJ/Kg, respectively and 275 MJ/kg for seeds (Omar and Nangia, 2023).

For example, if the same farm mentioned above consumes 36,706 MJ, and the maximum energy among tested farms is 70,000 MJ, then the saved energy is 33,294 MJ, and the energy pillar is 0.47.

Tomato productivity performance was quantified using a standardized yield efficiency ratio:

$$\text{Yield Performance} = \text{Actual Tomato Yield} / (\text{Maximum Attainable Tomato Yield}) \quad (6)$$

So, for the same farm the yield performance is calculated as 30 ton / 120 ton = 0.25. Farm-level economic performance in tomato production was assessed using the profit ratio:

$$\text{Profit Ratio} = \text{Net Profit} / \text{Total Revenue} \quad (7)$$

So, for the same farm the profit ratio is 19,500 JOD / 25,000 JOD = 0.78, JOD = Jordanian Dinar.

The carbon footprint of tomato production systems was estimated using an energy consumption-based approach. All energy consumptions, either using diesel or electricity were computed in MJ since the energy equivalent was 56 Megajoules (MJ)

For one liter of diesel in average and 3.6 MJ for one kilowatt (KW) of electricity (Yavuz et al., 2014):

$$\text{Number of Diesel Liters consumed} = \text{Total Energy} / 56 \quad (8)$$

For the same farm mentioned above consuming 36,706 MJ, the number of diesel liters is calculated as: 36,706 MJ / 56 = 655.46 Liters.

Since one liter of consumed diesel in the field produces 2.5 kg of CO₂ (Gautam et al., 2020), the CO₂ emissions for this farm = 655.46 Liters * 2.5 kg = 1,638 kg, while the maximum CO₂ emissions recorded is 3,125 kg.

The carbon-footprint pillar metric is calculated as the ratio between the reduced amount of CO₂ emission resulting from saved energy divided to the maximum amount of CO₂ emission recorded in the country.

$$\text{Carbon Footprint Pillar} = \text{Saved CO}_2 \text{ emission} / \text{Maximum CO}_2 \text{ emission} \quad (9)$$

For this farm, the carbon footprint = (3,125 – 1,638) / 3,125 = 0.47

So, for the same farm the WEFCE index was computed as each dimension was represented by a normalized pillar metric ranging from 0 to 1 and assigned a weight according to its relative importance within the nexus framework.

The overall index was calculated using a weighted aggregation approach:

$$\text{WEFCE} = (W \times 0.30) + (F \times 0.25) + (E \times 0.20) + (Ec \times 0.15) + (C \times 0.10) \quad (10)$$

Where W, F, E, Ec, and C represent the Water, Food, Energy, Economic, and Carbon Footprint pillar scores, respectively.

For the same farm mentioned above, the pillar scores were 0.23 for Water, 0.25 for Food, 0.47 for Energy, 0.78 for Economic Performance, and 0.47 for Carbon Footprint. After applying the corresponding weights, the weighted scores were 0.0699, 0.0625, 0.0940, 0.1170, and 0.0524, respectively.

The final WEFCE Nexus Index was obtained by summing these weighted contributions:

$$\text{WEFCE} = 0.07 + 0.06 + 0.09 + 0.11 + 0.04 = 0.37$$

The WEFCE index ranges from 0 to 1, where higher values indicate better sustainability performance and a stronger balance among resource use efficiency, economic viability, and environmental sustainability.

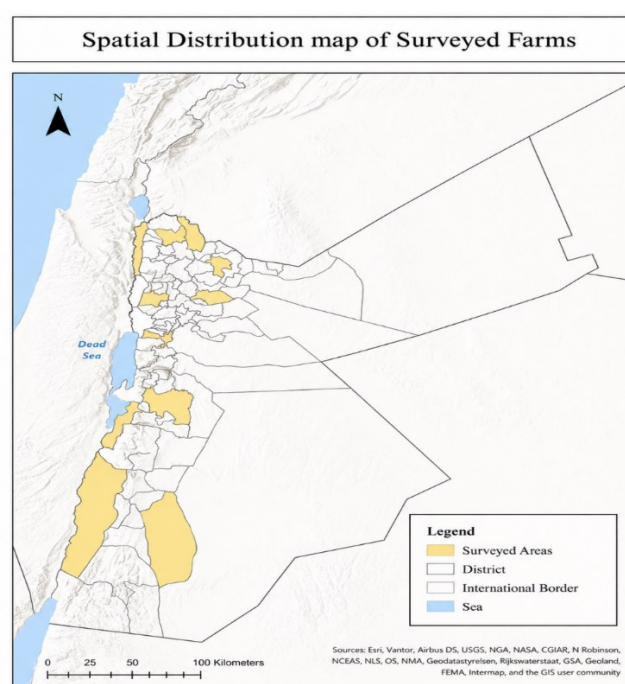


Figure 1 Spatial Distribution map of surveyed farms (Esri, [World Hillshade - Overview, https://www.arcgis.com/home/item.html?id=1b243539f4514b6ba35e7d995890db1d](https://www.arcgis.com/home/item.html?id=1b243539f4514b6ba35e7d995890db1d))

A set of quantitative indicators was selected to represent each WEFCE element. Water performance was assessed by comparing actual irrigation water use with estimated crop water requirements based on the FAO Penman–Monteith approach (Allen et al., 1998). Energy use included both direct energy consumption from diesel and electricity used for irrigation pumping and indirect energy embodied in agricultural inputs, particularly fertilizers. Food performance was evaluated using tomato yield relative to attainable production levels under Jordanian conditions. Economic performance was measured through farm profitability, considering revenues and production costs, while ecosystem sustainability was assessed using soil and irrigation water salinity as well as the carbon footprint associated with energy use.

Data quality control procedures were implemented prior to analysis to ensure the reliability and consistency of the dataset. Survey responses were screened for missing values, logical inconsistencies, and outliers. Reported values were cross-checked against established agronomic benchmarks and available national statistics, and all variables were converted into standardized measurement units. Farms with incomplete or inconsistent records were excluded from the final analysis.

Finally, descriptive and comparative statistical analyses were conducted to evaluate the distribution of WEFCE Nexus Index values across farms and production systems. Relationships among key indicators, particularly the interactions between water use, energy consumption, productivity, and the environmental impact, were also examined to identify major sustainability constraints and potential intervention pathways. This integrated methodological framework provides a robust basis for assessing agricultural sustainability and supporting evidence-based decision-making aimed at improving the resilience and resource-use efficiency of tomato production systems in Jordan.

3. RESULTS AND DISCUSSION

The distribution of agricultural production systems among the surveyed farms is nearly balanced between open-field and greenhouse cultivation. Open-land farming represents a slight majority (n = 171; 55.5%), while greenhouse systems account for a comparable proportion (n = 137; 44.5%) within the selected areas. This near-equal distribution indicates a diversified agricultural structure within the study area, where both traditional and controlled-environment farming systems are widely adopted. The marginal dominance of open-land agriculture suggests the continued importance of conventional practices; however, the substantial share of greenhouse cultivation reflects a significant shift toward more intensive and resource-controlled production systems.

From a (WEFCE) Nexus perspective, this duality is particularly important. Greenhouse systems are typically associated with higher energy inputs but improved water-use efficiency and productivity, whereas open-land systems generally require less energy but may exhibit lower control over water and environmental conditions. This balance provides a valuable basis for comparative analysis of resource use efficiency and sustainability across different agricultural systems.

Figure 2 illustrates the distribution of agricultural production systems across the surveyed regions. Greenhouse cultivation is concentrated primarily in Irbid and Ramtha, where it represents a substantial share of the surveyed farms. In contrast, open-field production dominates in most other locations, including Al-Qurayqirah Jamiyat, Northern Jordan Valley, Al-Karak, Mafraq, and Ma'an. Madaba is characterized predominantly by greenhouse production, although the sample size is relatively small. Several regions, including Al-Zarqa, Al-Qurayqirah/Mashariea, Irbid North Ghor, Ghor Al-Safi, and Balqa, are represented by only a limited number of observations and should therefore be interpreted with caution. The figure highlights clear regional differences in production systems, reflecting variations in climatic conditions, water availability, market orientation, and investment capacity.

The concentration of greenhouse systems in northern production areas suggests a greater adoption of intensive agricultural practices aimed at improving productivity and reducing exposure to climatic variability, while the predominance of open-field cultivation in other regions indicates continued reliance on conventional production methods.

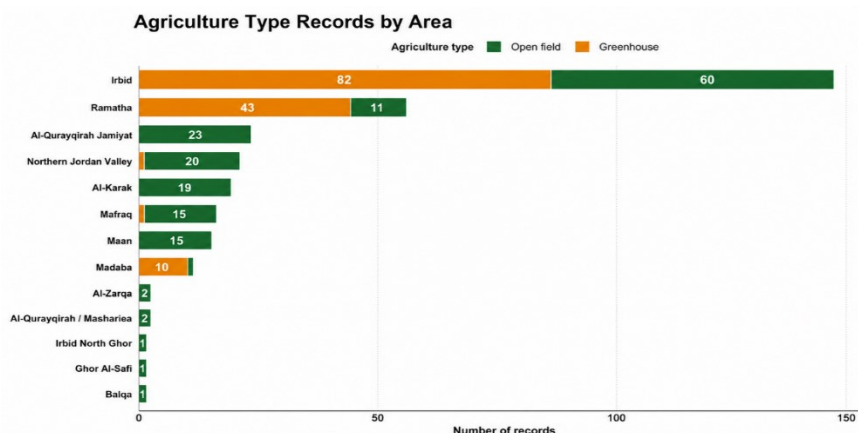


Figure 2 Agriculture type records by area

3.1. Irrigation Water Sources

The analysis of irrigation water sources indicates a strong dependence on groundwater as the primary source for agricultural activities. Groundwater accounts for most irrigation practices ($n = 210$; 68.18%), followed by surface water sources ($n = 92$; 29.87%). In contrast, rainwater harvesting ($n = 11$; 3.57%) and treated wastewater reuse ($n = 3$; 0.97%) represent only marginal contributions.

This distribution highlights a significant reliance on groundwater resources, suggesting potential pressure on aquifers and raising concerns regarding long-term groundwater sustainability. The relatively substantial use of surface water reflects the availability of alternative sources; however, its utilization remains considerably lower than groundwater. Meanwhile, the minimal adoption of harvested rainwater and treated wastewater indicate underutilization of potentially sustainable and non-conventional water resources.

The corresponding Figure 3 visually demonstrates this imbalance, with a dominant segment for groundwater and progressively smaller proportions for other sources. The distribution exhibits a clear skewness toward a single dominant category, emphasizing limited diversification in irrigation water sourcing.

3.2. Distribution of the WEFCE Nexus Index

The WEFCE Nexus Index values across the surveyed farms ranged from -0.40 to 0.98, with a mean value of 0.42 and a median of 0.414. Most observations were distributed between 0.30 and 0.60, indicating that most farms operate within the Vulnerable to Moderate Sustainability categories according to the adopted WEFCE classification framework (Figure 4).

Only a limited number of farms achieved WEFCE Index values above 0.60, reflecting relatively efficient resource management and balanced performance across Water, Energy, Food, Ecosystem, and Economic dimensions. Conversely, a smaller group of farms recorded values below 0.30, indicating significant resource-use inefficiencies and sustainability challenges. Overall, the distribution demonstrates considerable variability among farms, highlighting differences in management practices, resource availability, production systems, and environmental conditions across the study area.

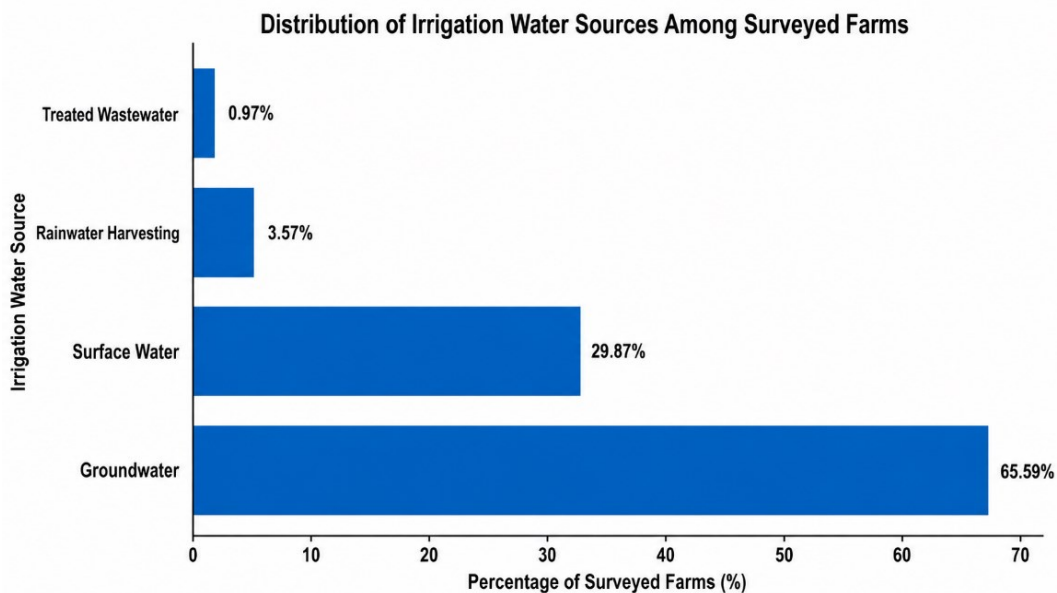


Figure 3 Irrigation Water Sources

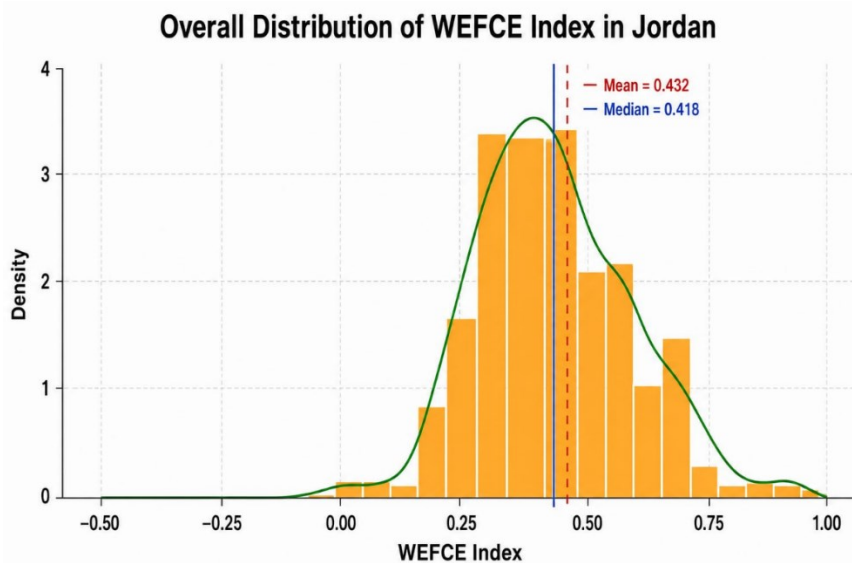


Figure 4 Distribution of the WEFCE Nexus Index

3.3. Water, Energy, and Environmental Constraints

Water scarcity emerged as the most important factor constraining sustainability. The results indicate that many farms apply irrigation volumes exceeding crop water requirements, resulting in low water-use efficiency and increased pressure on groundwater resources. Excessive irrigation also contributes to nutrient leaching and gradual soil salinization, thereby reducing the long-term sustainability of agricultural systems.

A strong interdependency between water and energy systems was observed throughout the analysis. Farms relying heavily on groundwater extraction generally exhibited higher energy consumption due to increased pumping requirements. Consequently, inefficient water management not only increases water demand but also elevates energy costs and carbon emissions. Diesel-powered irrigation systems were particularly associated with lower energy efficiency and higher environmental impacts.

Salinity was identified as a major ecosystem-related challenge. Moderate soil and irrigation water salinity dominated many surveyed farms, indicating the cumulative effects of groundwater use and limited natural leaching under arid climatic conditions. Salinity affects multiple elements of the WEFCE framework simultaneously by reducing water productivity, constraining crop growth and yield, increasing irrigation requirements, and indirectly raising energy consumption and greenhouse gas emissions.

3.4. Integrated WEFCE Performance

The analysis demonstrates that higher agricultural productivity does not necessarily correspond to higher sustainability performance. Many farms achieved relatively satisfactory tomato yields; however, these outcomes were often supported by excessive water use, intensive energy consumption, and elevated environmental pressures. These findings highlight the presence of important trade-offs within the WEFCE Nexus framework, where improvements in one element may occur at the expense of others. Overall, the results indicate that the principal sustainability challenges facing tomato production systems in Jordan are related to inefficient water use, energy-intensive irrigation practices, groundwater dependence, and salinity-related ecosystem degradation. The WEFCE Nexus framework proved effective in capturing these multidimensional interactions and identifying critical areas for intervention. The findings emphasize the need to shift from production-oriented agricultural systems toward integrated and resource-efficient management approaches capable of improving long-term sustainability and resilience under increasing resource constraints.

4. CONCLUSIONS

This study developed and applied an integrated WEFCE Nexus Index to evaluate the sustainability of tomato (*Solanum lycopersicum*) production systems in Jordan. Using field-level data collected from 308 farms across major agro-ecological regions, the study demonstrated that agricultural sustainability is shaped by the complex interactions among water use, energy consumption, food productivity, ecosystem health, and economic performance.

The results revealed that the sustainability performance of tomato farms in Jordan is generally moderate, with considerable variation among production systems and regions. Water scarcity emerged as the most critical constraint, while inefficient irrigation practices, dependence on groundwater pumping, and salinity-related ecosystem degradation were identified as the main drivers of unsustainable resource use. The analysis further showed that high agricultural productivity does not necessarily correspond to high sustainability, emphasizing the importance of improving resource-use efficiency rather than simply maximizing production.

Methodologically, the WEFCE Nexus Index proved to be an effective and practical tool for assessing farm-level sustainability under Jordan's water-scarce conditions. By integrating multiple elements into a single composite indicator, the framework captures the trade-offs and synergies among resource systems and provides a clear basis for comparing farms and identifying priority areas for intervention. Overall, the findings highlight the urgent need for integrated resource management strategies that improve irrigation efficiency, promote renewable energy adoption, strengthen groundwater governance, and support environmentally sustainable agricultural practices. The WEFCE Nexus framework developed in this study offers valuable guidance for policymakers, researchers, and development organizations seeking to enhance the resilience and long-term sustainability of agricultural systems in Jordan.

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ADVANCING WEF NEXUS–ALIGNED NON-CONVENTIONAL WATER RESOURCES AND RENEWABLE ENERGY FOR SUSTAINABLE AGRICULTURAL WATER MANAGEMENT

Abdelrahman Maki¹, Heba AlHariry², Georgina Robinson³, Leanne Casey⁴, Naomi⁵ Carrard and Mohamed AlHamdi⁶

ABSTRACT

Water, energy, food, and ecosystems are deeply interconnected, and pressures from climate change, population growth, and resource degradation are intensifying these linkages. Globally, nearly half of the population faces structural water scarcity, while agriculture responsible for about 70% of freshwater withdrawal, remains the largest and most vulnerable water user. At the same time, conventional irrigation systems are energy-intensive and often reliant on fossil fuels, contributing to greenhouse gas emissions and increasing production costs. In this context, non-conventional water resources (NCWR), such as treated wastewater and desalination, alongside renewable energy (RE), are gaining prominence as strategic solutions. However, their effectiveness depends not only on technological performance but on how they are embedded within governance, financial, and institutional systems. The WEF nexus received traction with policy makers and experts as way to facilitate regional and cross-sectoral co-operation. It is widely perceived that adopting a Nexus approach would allow governments to move beyond traditional sectoral thinking, and simultaneously achieve the policy objectives for energy, water, food and environmental security. This study aims to examine how WEF nexus–aligned NCWR and RE interventions can enhance agricultural water management and contribute to sustainable, resilient agrifood systems. Specifically, it seeks to identify proven and emerging technological pathways, assess enabling conditions and barriers for scaling, and provide policy-relevant insights to support the transition from pilot initiatives to system-level implementation across diverse regional contexts. The findings demonstrate that NCWR and RE can significantly enhance agricultural water security, productivity, and climate resilience, particularly when deployed within coherent system frameworks. A key insight is that technology alone is insufficient. Successful scaling depends on aligning NCWR and RE solutions with enabling environments, including fit-for-purpose regulatory frameworks, strong institutional coordination, sustainable financing mechanisms, and inclusive governance processes. Risk-based regulation, transparent monitoring, and stakeholder engagement are essential to build trust and ensure long-term viability. Moreover, WEF nexus approaches add value by making trade-offs explicit such as those between short-term productivity gains and long-term ecosystem sustainability and by supporting informed, equitable decision-making.

Keywords: WEF Nexus; Non-Conventional Water Resources; Renewable Energy; Agricultural Water Management; Water Scarcity; Sustainable Agriculture; Climate Resilience; Integrated Resource Management

¹ Land and Water Officer, Food and Agriculture Organization of the United Nations (UN FAO). Tunis. E-mail: abdourahman.maki@fao.org

² Land and Water Officer, Food and Agriculture Organization of the United Nations (UN FAO). Cairo, Egypt. E-mail: heba.alhariry@fao.org

³ Georgina Robinson, Institute for Sustainable Futures, University of Technology Sydney, Ultimo NSW, Australia

⁴ Leanne Casey, Institute for Sustainable Futures, University of Technology Sydney, Ultimo, Australia

⁵ Prof Naomi Carrard, Research Director, Institute for Sustainable Futures, University of Technology Sydney, Australia

⁶ Senior Land and Water Officer, Food and Agriculture Organization of the United Nations (UN FAO). Cairo, Egypt. E-mail: mohamed.alhamdi@fao.org

1. INTRODUCTION

Water, energy, food, and ecosystems are intrinsically interconnected, forming a complex system in which actions within one sector can generate cascading effects across others. The Water–Energy–Food–Ecosystem (WEFE) nexus has emerged as an important conceptual framework for understanding and managing these interdependencies, recognizing both the synergies and trade-offs that exist across sectors and scales (Hoff, 2011; Lazaro et al., 2022). By moving beyond fragmented and sector-specific approaches, the WEFE nexus promotes integrated resource management and supports more coherent decision-making processes. A fundamental principle of the nexus approach is that progress in one domain should not undermine the security or sustainability of another, emphasizing the need to explicitly account for cross-sector interactions in policy and practice (Mooren et al., 2025).

Agriculture represents a critical entry point for operationalizing the WEFE nexus. As the largest global consumer of freshwater and a major user of energy resources, the agricultural sector lies at the center of interactions between water security, energy demand, food production, and ecosystem health (FAO and UTS-ISF, 2025). Agricultural water use, including water for crop production, livestock, and on-farm operations therefore plays a pivotal role in determining the sustainability and resilience of agri-food systems. At the same time, increasing water scarcity, climate variability, environmental degradation, and growing competition among sectors are intensifying pressures on agricultural water resources and challenging conventional management approaches.

In response to these challenges, non-conventional water resources (NCWR) and renewable energy (RE) solutions are increasingly being promoted as key components of sustainable agricultural water management strategies. NCWR options, including treated wastewater reuse, desalination, rainwater harvesting, and managed aquifer recharge, offer opportunities to augment water supplies and reduce dependence on conventional freshwater resources. Similarly, renewable energy technologies can enhance the economic and environmental sustainability of water management systems by reducing operational costs and greenhouse gas emissions. However, despite their growing adoption, the effectiveness of NCWR and RE interventions cannot be assessed solely through a technological lens. In this regard, the WEFE nexus provides a valuable analytical framework for evaluating the broader implications of NCWR and RE interventions. The WEFE nexus functions simultaneously as a diagnostic tool to reveal trade-offs and synergies; a governance framework to support integrated decision-making, and a collaborative approach that promotes cross-sectoral coordination. Rather than assuming automatic co-benefits, the nexus approach facilitates the identification of trade-offs and synergies across water, energy, food, and ecosystem dimensions, thereby supporting more integrated and risk-informed planning. It also highlights the importance of governance arrangements, policy priorities, and incentive structures in shaping outcomes, determining how benefits and costs are distributed among stakeholders, and influencing the balance between short-term gains and long-term sustainability.

Against this backdrop, this paper applies an analytical nexus perspective to examine the role of WEFE Nexus-aligned NCWR and RE interventions in agricultural water management. The analysis draws on a technical synthesis and policy brief prepared by the University of Technology Sydney's Institute for Sustainable Futures (UTS-ISF) for FAO (FAO and UTS-ISF, 2026). By analyzing WEFE Nexus-aligned NCWR and RE impacts across water, energy, food, and ecosystem dimensions, the paper seeks to identify key trade-offs, synergies, key levers, and governance challenges associated with their implementation and scaling under increasing resource constraints and climate uncertainty.

2. METHODS

2.1 *Integrated WEFE Nexus-Based Comparative Assessment of Regional Evidence*

This paper draws on a comparative synthesis of evidence generated through five regional reviews conducted in 2025 covering Africa, Asia and the Pacific, Europe and Central Asia, Latin America and the Caribbean, and the Near East and North Africa (FAO and UTS-ISF, 2026).

The reviews were undertaken within the framework of the [FAO Inter-Regional Technical Platform on Water Scarcity \(iRTP-WS\)](#) to assess the role of NCWR and renewable energy in advancing sustainable agricultural water management through a WEFE nexus perspective.

The cross-regional comparative analysis was subsequently undertaken to identify common patterns, context-specific differences, and transferable lessons. By synthesizing evidence across diverse socio-economic, climatic, and institutional contexts, the methodology provides a global perspective on the opportunities and challenges associated with scaling WEFE-aligned NCWR and RE interventions in agriculture to support policymakers, practitioners, and development partners in designing integrated strategies that enhance water security, agricultural resilience, energy sustainability, and ecosystem health.

Particular emphasis was placed on understanding the governance, policy, financial, and institutional conditions associated with successful implementation and long-term sustainability (FAO and UTS-ISF, 2025).

2.2 Primary NCWR supply pathways

2.2.1 Treated wastewater reuse for irrigation

Wastewater reuse represents the most widely demonstrated NCWR pathway for primary water supply augmentation and substitution in agriculture across all five regions. Treated wastewater can be used for crop irrigation, livestock production, and other on-farm applications, provided that treatment levels meet fit-for-purpose quality requirements and relevant standards, such as WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater (WHO, 2006). The associated treatment technologies include a wide spectrum of systems, ranging from low-energy solutions such as stabilisation ponds and constructed wetlands to more advanced engineered processes, including activated sludge systems, membrane filtration technologies, electrochemical treatment.

Empirical evidence from regional reviews confirms that treated wastewater reuse is the most mature and scalable NCWR option for agricultural applications. However, its wider adoption is often constrained less by technological limitations than by social acceptance, regulatory frameworks, and institutional capacity, particularly where wastewater is used in food production. Where implemented at scale, wastewater reuse provides a reliable irrigation water source while generating multiple co-benefits across the WEFE nexus. These include reduced pollutant discharge into receiving ecosystems, partial substitution of freshwater abstractions, and nutrient recycling, particularly nitrogen and phosphorus, which can reduce dependence on synthetic fertilisers. Despite these benefits, global reuse remains limited, with only approximately 11% of wastewater being safely reused, indicating substantial untapped potential for expansion under appropriate enabling conditions (Jones et al., 2021).

The application of wastewater reuse systems varies significantly across regions (Table 1), reflecting differences in technological choices, regulatory maturity, and socio-economic conditions. Results highlights the role of low-energy treatment systems in supporting agricultural production through nutrient recovery, while also revealing important environmental trade-offs. In contrast, many African urban contexts illustrate the persistence of informal reuse practices driven by necessity, alongside associated public health concerns. Meanwhile, the European and Central Asian region demonstrates that even well-developed regulatory frameworks may face implementation and social acceptance challenges.

Table 1: Summary Table of Regional Evidence on Wastewater Reuse Systems

Main System Characteristics	Key Benefits of these Characteristics	Key Risks / Constraints	Main Policy Implications
Low-energy treatment systems (e.g., stabilization ponds, constructed wetlands) used in agricultural peri-urban zones	Reduced fertilizer demand and costs due to nutrient recycling; lower GHG emissions from fertilizer production and use	Soil salinity buildup; nutrient overloading affecting soil health and crop productivity	Need for context-specific reuse standards and integrated soil–crop management practices
Informal reuse of untreated or partially treated wastewater in urban agriculture	Supports food security and livelihoods; provides water and nutrient access under scarcity conditions	High public health risks (e.g., cholera, diarrhea diseases); exposure to pathogens	Priority is transitioning from informal unsafe reuse to regulated, safe systems rather than promoting uptake
Formalized regulatory frameworks for treated wastewater reuse	Strong institutional and legal frameworks enabling safe reuse systems	Low adoption (<25%); public perception and trust issues; uneven implementation across countries	Main challenge is implementation capacity, stakeholder trust, and operationalization of existing policies rather than policy design

Case Study 1: Triangular Cooperation Project (ADB)

People's Livelihoods Initiative through Water-Energy-Food Nexus in the Mekong Region (P-LINK) (Cambodia · Lao PDR · Thailand · Vietnam) The P-LINK (People's Livelihoods Initiative through Water-Energy-Food Nexus in the Mekong Region) project demonstrates how NCWR and renewable energy solutions can be implemented within a transboundary WEFE nexus framework. Implemented across Cambodia, Lao PDR, Thailand, and Vietnam, the initiative was established in response to growing competition over water, energy, and food resources in the Lower Mekong Basin, driven by hydropower expansion, population growth, economic development, and increasing climate variability. Funded by the Republic of Korea and implemented through a South–South and triangular cooperation model under the United Nations Office for South-South Cooperation (UNOSSC, 2023), the project seeks to strengthen water, energy, and food security while improving livelihoods in vulnerable communities.

The project operationalised the WEFE nexus through country-specific pilot interventions tailored to local conditions. Relevant examples include solar-powered water treatment systems in Cambodia and saline groundwater desalination combined with brine reuse for aquaculture in Vietnam. These pilots illustrate how renewable energy can support alternative water supply solutions while generating co-benefits for agricultural production and rural livelihoods. A key challenge encountered during implementation was the lack of compatibility between existing energy and water infrastructure, such as differing grid standards in Vietnam. Addressing these issues required close coordination among multiple ministries and agencies, highlighting the importance of institutional coherence when scaling nexus interventions. The project also faced risks of stakeholder fatigue, which were mitigated by adopting a demand-driven approach and embedding activities within national development and planning frameworks.

The main lesson from P-LINK as illustrated in (Table 2) is that successful deployment of NCWR and renewable energy technologies in transboundary river basins depends not only on technological innovation but also on effective governance mechanisms. The project demonstrates that regional platforms such as the Mekong River Commission play a critical role in facilitating dialogue, aligning national priorities, and managing trade-offs between water, energy, food, and ecosystem objectives. The experience suggests that investments in governance and coordination platforms should precede or accompany technology deployment to ensure that WEFE nexus interventions deliver sustainable and equitable outcomes across shared river basins.

Table 2: Factors Influencing the Scaling of NCWR and Renewable Energy Solutions through the WEFE Nexus in Transboundary River Basins

P-LINK: Triangular Cooperation in the Lower Mekong Basin [RAP] Various technologies – desalination, water treatment with RE	
WEFE - Water · Energy · Food Scale - Transboundary Technology - Solar-powered water treatment (Cambodia); solar desalination with brine reuse for aquaculture (Vietnam) RE - Solar PV - fully integrated Locations - Cambodia · Lao PDR · Thailand · Vietnam	
TRIGGER	Increased competition over water, energy, and food driven by hydropower expansion and seasonal climate extremes; lessons from predecessor programmes (WE4F, PAEGC) provided a ready policy solutions which accelerated adoption.
STREAMS	The Mekong River Commission (MRC's) Basin Development Strategy aligned national ministries across four countries with Republic of Korea funding and UNOSSC frameworks, coupling the problem, policy, and politics streams into a single coordinated platform.
BARRIERS	Grid incompatibility between energy and water infrastructure from (22kV to 380kV in Vietnam), was resolved through cross-ministry coordination, demonstrating that small-scale pilots require institutional coherence across sectors; stakeholder fatigue was addressed through demand-driven design embedded in national planning frameworks.
LESSONS	Demonstrates that NCWR-RE solutions for agricultural water use in transboundary contexts require a shared governance platform to prevent decisions being made in isolation, provided by the MRC. Future WEFE alignment for NCWR in agriculture must invest in platforms such as the MRC before technology deployment.
WEFE Reflection: Transboundary water challenges are rarely solved through technology alone. As competition over water, energy, and food intensifies, the policy window emerges when countries recognize that isolated decisions impose costs beyond national borders. The Lower Mekong experience shows that embedding NCWR and renewable energy solutions within a shared WEFE governance platform transforms pilot technologies into basin-wide opportunities, reducing institutional fragmentation and enabling coordinated resource management across sectors and countries.	

2.2.2 Desalination and Brackish Water Treatment for Agriculture

(Reverse osmosis (RO), thermal desalination (multi-stage flash and multi-effect distillation), electrodialysis, and forward osmosis (FO))

Desalination and brackish water treatment are climate-independent NCWRs that can augment water supplies in water-scarce regions. However, their use in agriculture remains selective due to high capital, operational, and energy costs.

Evidence from NENA and Europe suggests that desalination is most viable for high-value crops, protected agriculture, and peri-urban systems, particularly when combined with renewable energy and blended with other water sources to reduce costs and salinity (FAO and UTS-ISF,2025)

Unlike treated wastewater, desalinated water contains negligible nutrients, increasing reliance on synthetic fertilizers and associated costs and emissions. While this limits its WEFE nexus benefits, controlled production systems such as greenhouses, hydroponics, and precision fertigation can take advantage of its consistent water quality and support higher productivity. Therefore, from a WEFE perspective, desalination improves water security and reduces pressure on freshwater resources but involves significant trade-offs, including high energy demand, costs, and environmental risks from brine disposal. Consequently, its successful deployment depends on renewable energy integration, supportive policies, targeted investments, and effective environmental safeguards. Overall, desalination is best considered a targeted solution for high-value agricultural systems in water-scarce regions rather than a broadly applicable strategy for agricultural water supply augmentation.

Case Study 2: Torrevieja Desalination Plant, Spain

Spain has long prioritized the development of non-conventional water resources (NCWRs) due to its comparatively high levels of water scarcity within Europe. As a result, treated wastewater reuse and seawater desalination have become integral components of national and regional water management

strategies, supported by relatively strong governance frameworks and public investment (Navarro, 2018; Martínez-Medina et al., 2024).

The Torrevieja Desalination Plant, located on Spain's southeastern Mediterranean coast, is the largest desalination facility in Europe, producing approximately 240,000 m³ of freshwater per day. The plant supplies water for both urban and agricultural uses, helping address chronic water scarcity and seasonal demand fluctuations associated with tourism and recurrent droughts. Although domestic consumption is prioritised during peak summer periods, the facility primarily supports the irrigation of high-value agricultural crops, including citrus fruits and vegetables destined for export markets.

From a WEFE nexus perspective as demonstrated in Table 3, the Torrevieja experience highlights several key lessons for the deployment of desalination within the WEFE nexus. First, desalination can serve as an effective drought resilience strategy by simultaneously supporting agricultural production and urban water supply. Second, despite substantial public investment and subsidies, affordability remains a major constraint, particularly when desalinated water competes with lower-cost conventional sources such as groundwater creating strong interdependencies between water and energy systems. The increasing integration of renewable energy sources, particularly solar power, offers opportunities to reduce operational costs and carbon emissions, thereby improving overall sustainability.

Third, the sustainability of desalination depends increasingly on coupling with renewable energy systems to reduce energy-related costs and emissions. Finally, while ongoing investments and expansion plans demonstrate the growing strategic importance of desalination, environmental considerations remain a critical aspect of desalination development. While technology alleviates pressure on freshwater ecosystems, brine discharge poses potential risks to marine habitats through increased salinity levels and associated ecological impacts. Consequently, continuous environmental monitoring and regulatory oversight are required to minimize adverse effects and ensure compliance with environmental standards.

Table 3: Factors Influencing the Scaling of NCWR and Renewable Energy Solutions in Torrevieja Desalination Plant, Spain

CASE STUDY 2 Torrevieja Desalination Plant [ECA] Alicante, Spain	
WEFE -Water-Energy-Food Scale -National Technology -Seawater reverse osmosis (RO) RE -Fossil-dominated, Solar PV planned	
TRIGGER	The AGUA Programme abandoned the Ebro inter-basin transfer and made large-scale desalination the only politically viable alternative.
STREAMS	Spanish Ministry of Agriculture, Acciona (private operator), and EU environmental monitoring were coupled through a (Private Public Partnership (PPP) concession model backed by state subsidies, translating political will into durable operational infrastructure.
BARRIERS	High operational cost of RO desalination was addressed through state subsidies, though farmer resistance to water pricing persists; fossil energy lock-in from original design now constrains RE retrofitting, controversy faced over solar PV installation due to competition for land.
WEFE Reflection: High-cost, high-risk water infrastructure is rarely politically attractive. Yet water scarcity creates a policy window: when choices narrow to inter-basin transfers or desalination, transformative investment becomes unavoidable. Embedding RE from the outset through a WEFE nexus-aligned design avoids financial and political controversy.	

2.3 Supplementary NCWR Pathways for Resilience and Buffering

Rainwater harvesting, managed aquifer recharge and small-scale reuse (Rainwater harvesting systems, atmospheric (fog) moisture harvesting systems, managed aquifer recharge: infiltration basins, recharge wells, small-scale drainage reuse). Across regions, these NCWRs function primarily as supplementary water sources that enhance the resilience of agricultural water systems rather than serving as standalone alternatives to conventional supplies. Their principal contribution lies in buffering seasonal and interannual variability, reducing exposure to climate-related water risks, alleviating pressure on

overexploited surface and groundwater resources, and supporting broader WEF nexus objectives. Evidence from Africa (RAF), Asia and the Pacific (RAP), and Latin America and the Caribbean (LAC) (Table 4) indicates that these approaches are most effective when integrated within broader water resource management frameworks and supported by enabling institutional arrangements, local governance mechanisms, and agricultural extension services. While their direct volumetric contribution to agricultural water supply is generally limited and highly dependent on local climatic, hydrological, and environmental conditions, their strategic value lies in enhancing system flexibility, improving drought preparedness, and increasing adaptive capacity in climate-vulnerable regions.

Table 4: Cross-Regional Synthesis of Supplementary Non-Conventional Water Resources for Agricultural Water Supply and Resilience Enhancement

NCWR Option	Primary Function	Regional Evidence	Main Benefits	Key Limitations	Policy and Management Implications
Rainwater Harvesting	Supplementary water supply and drought buffering	Widely reported in RAF, RAP, and LAC, particularly in rainfed and smallholder systems	Enhances water availability during dry periods, reduces runoff losses, improves resilience to rainfall variability	Highly dependent on rainfall patterns, storage capacity, and seasonal variability; limited volumetric contribution	Most effective when integrated into broader water management and climate adaptation strategies rather than treated as a primary water source
Atmospheric Moisture Harvesting (Fog Harvesting)	Localized supplementary water supply	Demonstrated in specific coastal and mountainous areas of RAP and LAC where climatic conditions are favorable	Provides an alternative water source in water-scarce environments with minimal energy requirements	Strongly dependent on local climatic conditions and generally provides limited volumes	Suitable for niche applications and vulnerable communities rather than large-scale agricultural supply
Managed Aquifer Recharge (MAR) (Infiltration basins, recharge wells)	Groundwater replenishment and storage enhancement	Applied across RAF, RAP, and LAC to improve groundwater reliability and drought resilience	Enhances groundwater security, reduces aquifer depletion, buffers climate variability	Requires suitable hydrogeological conditions, monitoring systems, and institutional capacity	Should be incorporated into basin-scale water planning and groundwater management frameworks
Small-Scale Drainage Water Reuse	Water recovery and local supply augmentation	Reported in water-scarce agricultural systems across multiple regions	Improves water productivity and reduces pressure on freshwater withdrawals	Water quality concerns, salinity accumulation, and infrastructure requirements may limit expansion	Requires monitoring, water quality management, and integration with sustainable irrigation practices
Cross-Cutting Regional Findings	Resilience enhancement rather than primary supply substitution	Consistent evidence from RAF, RAP, and LAC	Strengthens resilience, reduces climate risk, alleviates pressure on conventional water resources, and supports WEF nexus objectives	Volumetric contributions are typically modest and highly context dependent	Greatest value lies in complementing conventional supplies within diversified water portfolios rather than replacing them

The effectiveness of these approaches is strongly context dependent. Rainwater and atmospheric water harvesting systems are constrained by precipitation patterns, humidity conditions, and storage capacity, whereas managed aquifer recharge and drainage water reuse depend on hydrogeological suitability, water quality considerations, and monitoring capacity. Consequently, their contribution to agricultural water security varies considerably across locations and production systems.

3. RESULTS AND DISCUSSION

The findings indicate that while appropriate technologies are essential for the development and deployment of NCWRs, their successful scaling depends on governance, institutional, financial, and environmental conditions that enable their sustainable implementation and long-term operation. Across all NCWR categories, enabling factors consistently include the presence of clear regulatory frameworks, sustainable financing mechanisms, effective monitoring systems, and integration within broader water resource management strategies.

For wastewater reuse, the evidence highlights that risk-based, fit-for-purpose regulatory approaches, clearly defined institutional responsibilities, nutrient recovery considerations, lifecycle financing, and transparent monitoring systems are critical for safe and effective implementation (Figure 1). These factors support both operational sustainability and public acceptance. However, wastewater reuse remains constrained by weak or overly restrictive regulatory frameworks, chronic underinvestment in operation and maintenance, limited public trust, and environmental risks associated with salinity accumulation and nutrient imbalances. These findings suggest that the primary challenges are institutional and governance-related rather than technological.

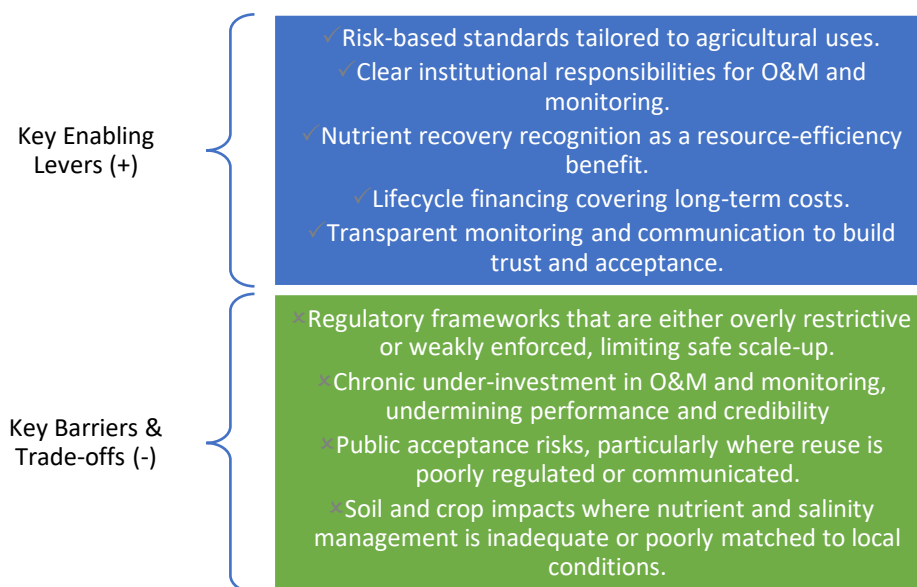


Figure 1. Wastewater Reuse: Key Enabling Levers vs. Barriers

Similarly, the viability of desalination for agricultural use depends on supportive policy and investment environments (Figure 2). Targeted subsidies, renewable energy integration, particularly solar energy, and blending strategies to manage salinity and nutrient deficiencies can improve economic and environmental performance. Nevertheless, high capital and operational costs remain significant barriers, limiting adoption primarily to high-value agricultural systems. Additional challenges include environmental concerns associated with brine disposal, and the absence of nutrients in desalinated water, which increases reliance on synthetic fertilisers and may weaken WEF nexus synergies compared with wastewater reuse.

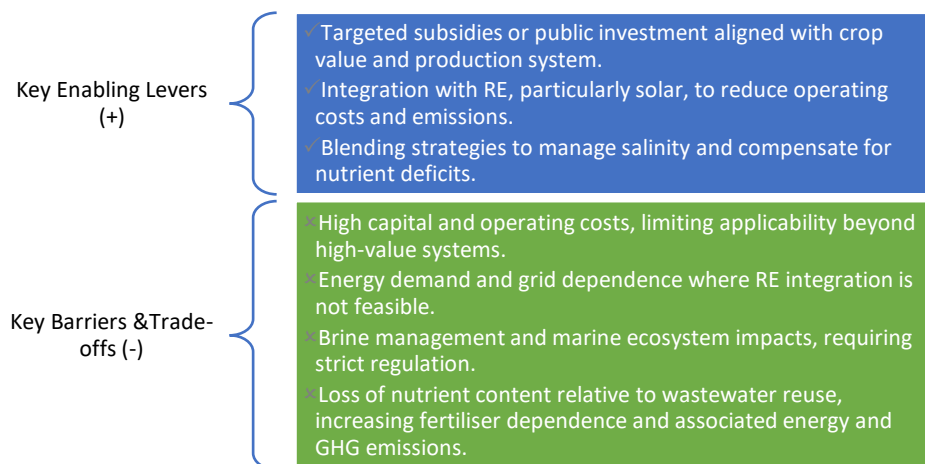


Figure 2. Desalination Key Enabling Levers vs Barriers.

For supplementary NCWR options, effectiveness is strongly linked to their integration within basin-scale planning and broader land and water management strategies. Cross-regional evidence (Figure 3) analysis further demonstrates that each supplementary NCWR option presents distinct opportunities and limitations. Rainwater harvesting and atmospheric moisture harvesting offer decentralized and relatively low-cost solutions but remain highly dependent on local climatic conditions and available storage capacity. Managed aquifer recharge can enhance groundwater security and seasonal water availability but requires suitable hydrogeological conditions, adequate water quality controls, and sustained financial resources. Across regions, the most successful examples are those embedded within integrated water management frameworks that recognize these options as complementary resilience measures rather than standalone solutions to water scarcity.

Overall, the results suggest that the long-term sustainability and scalability of NCWRs are determined primarily by governance quality, institutional coordination, financial sustainability, environmental safeguards, and stakeholder engagement. Technologies alone are insufficient to achieve water security objectives unless supported by enabling policy environments and integrated management approaches that account for local environmental, economic, and social conditions.

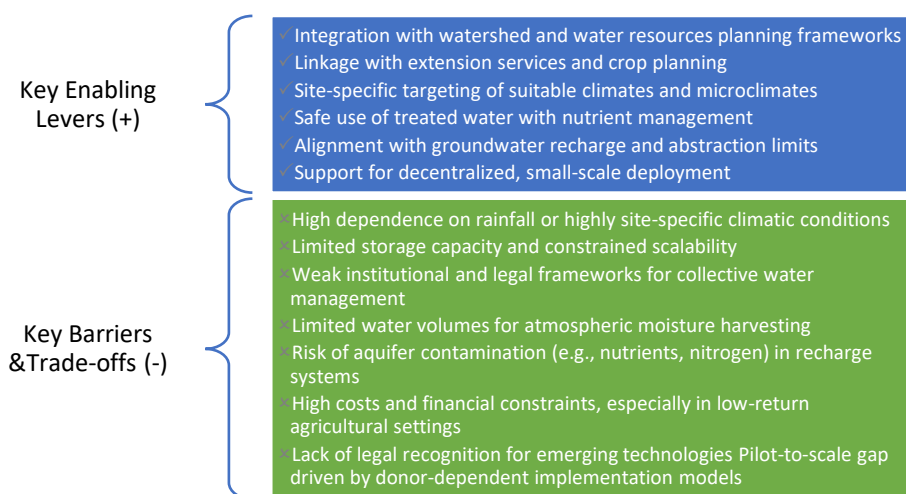


Figure 3. : Applicability, Levers, Barriers and WEF Nexus Alignment of Supplementary Water Resources

CONCLUSIONS

This paper examined the role of NCWRs and renewable energy in advancing sustainable agricultural water management through a WEF nexus perspective. Drawing on comparative evidence from five global regions, the analysis demonstrated that NCWRs and RE can substantially enhance water security, agricultural productivity, and climate resilience when implemented within integrated governance and management frameworks. The findings indicate that treated wastewater reuse represents the most mature and scalable NCWR pathway for agriculture, offering multiple co-benefits. In contrast, desalination provides a reliable but more selective solution, primarily suited to high-value agricultural systems and water-scarce regions where renewable energy integration and supportive policy frameworks can offset economic and environmental constraints. Supplementary NCWR options, contribute most effectively as “resilience-enhancing measures” within diversified water portfolios rather than as primary water supply substitutes.

Across all technologies, successful scaling depends not only on technical performance but also on enabling governance conditions, including clear regulatory frameworks, institutional coordination, sustainable financing, environmental safeguards, and stakeholder engagement. The findings further confirm the value of the WEF nexus in identifying synergies, managing trade-offs, and supporting integrated decision-making across sectors. Future work should focus on developing quantitative WEF nexus assessment tools to evaluate the cumulative impacts of NCWR and RE interventions, generating stronger evidence on their long-term economic, environmental, and social performance, and identifying governance and financing models that can facilitate the transition from pilot projects to large-scale implementation. Particular attention should also be given to assessing ecosystem impacts, climate adaptation benefits, and pathways for integrating NCWR and renewable energy solutions into national agricultural water management strategies.

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IWEF-BASED INTEGRATED NEXUS ASSESSMENT AT SUB-NATIONAL SCALE OF THE CROCODILE RIVER CATCHMENT.

Nwabisa Zingelwa-Masekwana¹ Cuthbert Taguta², Michael Van der Laan^{1,3}, Sue Walker^{1,4}

ABSTRACT

Sustainable management of water, energy, and food (WEF) systems is challenging, especially in semi-arid regions like South Africa. This study used the WEF Nexus framework to analyse sub-national planning scales in the Crocodile River Catchment, specifically in Mpumalanga Province and the Ehlanzeni District Municipality. The Analytical Hierarchy Process (AHP)-based integrative analytical tool iWEF 1.0 decision-support tool was used to evaluate WEF sustainability using a participatory, stakeholder-driven methodology. A structured questionnaire with a 5-point Likert scale (poor, low, good enough, very good, excellent) was administered to multi-sectoral stakeholders to collect data on WEF resource security as input data. The responses were utilized to create pairwise comparison matrices (PCMs), based on stakeholders' pairwise judgments of six indicators that assessed the availability and accessibility of water (W), energy (E), and food (F). The PCMs were used to assess the state of the WEF nexus as measured by normalised sector-specific and integrated WEF nexus composite indices. The integrated WEF nexus composite index values are categorised into ranges from 0.048 to 0.107 as unsustainable, 0.108 to 0.167 as marginally sustainable, 0.168 to 0.226 as moderately sustainable, and 0.226 to 0.286 as highly sustainable in the iWEF tool. The analyses indicated moderate WEF sustainability with nexus composite index values of 0.185 for Mpumalanga Province and 0.210 for Ehlanzeni District Municipality. Water availability exhibited comparatively stronger performance, while energy availability and accessibility emerged as dominant constraints. Food insecurity was primarily associated with access-related factors rather than production limitations. This is consistent with municipal and provincial government efforts to formally furnish water and electricity resources; nevertheless, the situation differs in the rural outskirts, as indicated by Mpumalanga Province's worse index performance. The study reveals that participative, AHP-based nexus evaluations provide a comprehensive tool for discovering sectoral imbalances which improve integrated WEF resource planning and guide nexus actions at sub-national levels.

Keywords: Analytical Hierarchy Process, Consistency Ratio, Pairwise Comparison Matrix, Water-Energy-Food Nexus

1. INTRODUCTION

Strategic sectors such as water, energy, and food are directly interconnected and interdependent within the water–energy–food (WEF) nexus (Liu et al., 2018). Sustainable management of WEF resources has become a critical development challenge, particularly in water-scarce and socio-economically diverse regions such as South Africa (Khofi et al., 2025). Increasing pressures from climate variability, population growth, rapid urbanisation, and competing sectoral demands have intensified the interdependencies among WEF systems (Simpson & Jewitt, 2019). Fragmented sector-based planning approaches have proven inadequate for addressing these interconnected challenges, highlighting the need for integrated resource management frameworks capable of supporting coordinated planning and governance (Mantlana et al., 2023). The WEF nexus framework has emerged as an important integrative approach for improving resource-use efficiency, resilience, and sustainability across multiple

¹ NRE, Arcadia, Pretoria, South Africa: Email: masekwanan@arc.agric.za;

² Centre for Transformative Agriculture and Food Systems, School of Agriculture and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa

³ University of Pretoria, South Africa: VanderLaanM@arc.agric.za

⁴ University of the Free State, Bloemfontein, South Africa WalkerS@arc.agric.za;

spatial scales (Liu et al., 2018; Nhamo et al., 2020). At sub-national scales, understanding local resource interactions and stakeholder perceptions is particularly important for improving service delivery, governance coordination, policy implementation, and resource sustainability outcomes (Mabhaudhi et al., 2023). Provincial and district-level assessments are relevant in South Africa, where governance responsibilities for water, energy, and food systems are distributed across multiple institutional and administrative structures (Taguta et al., 2026).

Operationalising the WEF nexus remains challenging due to difficulties in translating qualitative stakeholder knowledge into quantitative, comparable metrics to support planning and decision-making (Khofi et al., 2025). In response, several integrated analytical approaches combining participatory assessments, multi-criteria decision-making techniques, and integrated sustainability indicators have been developed (Yang et al., 2026). These approaches often utilise Analytical Hierarchy Process (AHP)-based methods to evaluate resource interactions and sustainability trade-offs. Participatory stakeholder engagement is increasingly recognised as a critical component of WEF nexus assessments, as it incorporates local knowledge and captures context-specific resource challenges (Walker et al., 2024). Furthermore, it improves the relevance of decision-support systems (Endo et al., 2017). Stakeholder perception indicators are widely recognised as valuable inputs for integrated nexus assessments, especially where quantitative data is limited or fragmented (Albrecht et al., 2018).

The iWEF 1.0 (<https://www.iwef.app/>) tool is a geospatial, web-based, integrative analytical platform designed to facilitate the integrated assessment of WEF resources and resilience-building and adaptation initiatives and strategies (Taguta et al., 2023). The integrative analytical Water–Energy–Food (iWEF) 1.0 tool is a geospatial web-based analytical platform designed to facilitate integrated assessment of WEF resources, resilience-building strategies, and sustainability planning (Taguta et al., 2023). The tool applies the AHP technique to generate composite indices reflecting resource availability, accessibility, sufficiency, productivity, and relative sectoral performance (Nhamo et al., 2020). The incorporation of stakeholder-based data and consistency evaluation procedures enables the iWEF tool to perform the integrated assessment of WEF sustainability (Taguta et al., 2023).

METHODOLOGY

Study area and stakeholder engagement.

The study was conducted within the Crocodile River Catchment (Figure 1) in Mpumalanga Province, South Africa, focusing on two sub-national spatial scales: Mpumalanga Province and the Ehlanzeni District Municipality (Figure 2). The Crocodile River Catchment supports intensive agricultural production, industrial development, urban settlements, and ecological systems, making it highly relevant for integrated WEF nexus assessment.

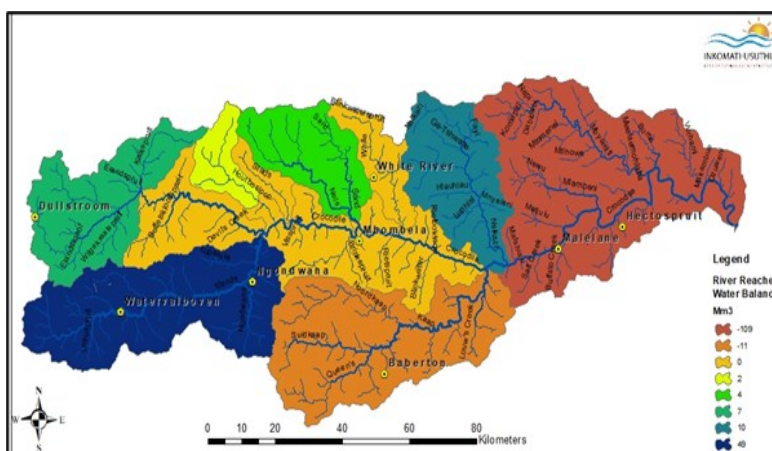


Figure 1. The Crocodile River Catchment as depicted by the Inkomati-Usuthu Catchment Management Agency (IUCMA, <https://iucma.co.za/>)

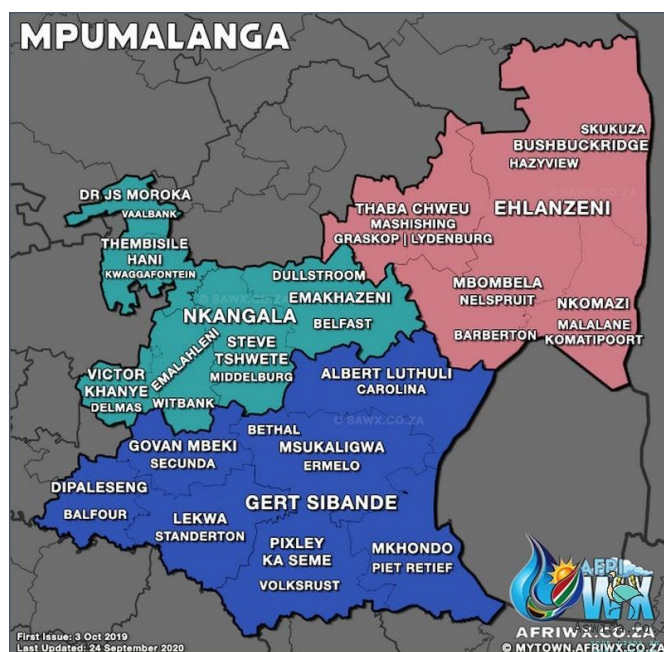


Figure 2. The Mpumalanga Province of South Africa and the municipal districts including Ehlanzeni District, home to the city of Mbombela (<https://aswica.co.za/discover-the-amazing-mpumalanga-province-map/>).

Stakeholders were engaged through Crocodile River Catchment forums coordinated by the Inkomati–Usuthu Catchment Management Agency (IUCMA). Participants included representatives from irrigation boards, small-scale and commercial farmers, municipalities, agriculture, energy providers, private sector institutions, and local government departments. Purposive stakeholder sampling was used to ensure representation across major WEF sectors and governance structures.

Questionnaire design and scoring

A structured questionnaire was developed to capture stakeholders' perceptions of the sustainability of water, energy, and food resources. The questionnaire focused on two core dimensions within each sector: availability and accessibility. The comparison of the relative importance or performance of the water, energy, and food sectors and their indicators, namely water availability (WAv), water access (WAc), energy availability (EAv), energy access (EAc), food availability (FAv), and food access (FAc) was assessed. The definition of resource (water, energy, food) availability in this study is the response to the rating of sufficiency to the stakeholder. Similarly, the definition of resource access is the response to the rating of accessibility to water to the stakeholder. The iWEF tool then aggregated these normalised indices derived from the PCMs and the weighted variables to determine integrated WEF nexus composite indices for both the Mpumalanga Province and the Ehlanzeni District Municipality. Responses were collected through pairwise comparison of the six WEF-related indicators using a five-point Likert scale consisting of poor, low, good enough, very good, and excellent categories. To ensure compatibility with the AHP methodology and the iWEF tool, responses were standardized to the nine-point Saaty scale (Saaty, 1980).

Pairwise Comparison Matrix Development

Stakeholder responses were translated into pairwise comparison matrices (PCMs) consistent with the Analytical Hierarchy Process (AHP) methodology proposed by Saaty (1980) and the iWEF tool's data interface. The consistency of the initial PCMs were evaluated using the Consistency Ratio (CR) derived from the Analytic Hierarchy Process (AHP) methodology. The consistency of stakeholder judgments, i.e., the PCMs, was evaluated using the Consistency Index (CI) and Consistency Ratio (CR) (Equation 1 and 2):

Where: CI = Consistency Index (CI) = $(\lambda_{max} - n) / (n - 1)$; -----(1)

- λ_{max} = Principal eigenvalue of the pairwise comparison matrix
- n = Number of criteria or indicators compared

Where: CR = The Consistency Ratio (CR) = CI / RI ----- (2)

- CI = Consistency Index

RI = Random Index corresponding to the matrix size n . CR values below 0.10 (10%) indicate acceptable consistency and reliability of pairwise judgements, while values exceeding 0.10 (10%) indicate inconsistent responses requiring revision (Saaty, 1980). Where inconsistent PCMs are identified, the tool reports consistency ratios above the acceptable threshold of 10%, and the matrices have to be iteratively reviewed with stakeholders using automated tools such as the AHP Priority Calculator (AHP-OS) (AHP-OS) <https://bpmsg.com/ahp/ahp-calc.php> to identify outlier judgements.

iWEF Tool Assessment

The AHP method in the iWEF tool enables integrated and systematic comparison of multiple criteria, in this case, the six indicators, through the determination of normalised indices representing the relative importance of indicators. The consistent PCMs were subsequently used in the iWEF tool to calculate normalised indices and integrated WEF nexus composite indices. The iWEF tool aggregated the normalised indices derived from the PCMs and weights to generate integrated WEF nexus composite indices according to the following expression:

Where WEF index = $\sum_{i=1}^n (w_i x_i)$ ----- (3)

- w_i = Weight assigned to indicator i derived from the AHP pairwise comparison matrix
- x_i = Normalised value of indicator i
- n = Total number of indicators included in the assessment

The resulting integrated WEF nexus composite indices are categorised (see Table 1) according to the sustainability scale proposed by Taguta et al. (2023) and Nhamo et al. (2020).

Table 1. The categorisation of the Integrated WEF Nexus Composite Index Ranges into sustainability categories (Taguta et al., 2023).

Composite Index Range	Sustainability Category
0.048–0.107	Unsustainable
0.108–0.167	Marginally sustainable
0.168–0.226	Moderately sustainable
0.227–0.286	Highly sustainable

2. RESULTS

The stakeholder-derived pairwise comparison matrices yielded acceptable consistency ratios ($CR < 10\%$), confirming the reliability, logicity and rationality of stakeholder judgments of the six WEF-related indicators. The CR values for the final PCMs were below 10% for both Mpumalanga Province (2.3%) and the Ehlanzeni District (2%) (Table 2). This shows that the final PCMs were consistent according to AHP standards (Saaty, 1980). The pairwise judgements in the consistent PCMs are referencing the row indicators to the column indicators in Table 2. For example, the stakeholders in the Mpumalanga province ranked Wav higher than FAv by a factor of 2 in the AHP scale, and the Ehlanzeni district ranking for the same indicators was ranked higher by a factor of 5.

The iWEF tool used the AHP method to generate normalised indices reflecting the relative performance of water, energy, and food resource availability and accessibility within both case study areas (Taguta et al., 2023). The descending order of performance for the AHP-based indices of the six indicators obtained from the iWEF tool for Mpumalanga province was EAc (0.218), WAv (0.201), EAv (0.180), WAc (0.163), FAc (0.129) FAv (0.109) with an integrated WEF nexus composite index of 0.185 (Table 3; Figure 3). The Ehlanzeni District showed values of the normalised indices were 0.394 (WAv), 0.174 (EAc), 0.134 (EAv), 0.115 (WAc), 0.101 (FAc), and 0.082 (FAv), yielding an integrated WEF nexus composite index of 0.210 (Table 3; Figure 3).

Table 2. The final consistent Pairwise Matrix Comparison (PCM) of WEF indicators in the Mpumalanga Province (not in brackets) and Ehlanzeni district municipality (in brackets).

Water-Energy-Food (WEF) indicators	Wav	Wac	Eav	EAc	FAv	FAc
WAv	1 (1)	1 (4)	1 (3)	1 (2)	2 (5)	2 (4)
WAc	1 (0.25)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
EAv	1 (0.3)	1 (1)	1 (1)	1 (1)	2 (2)	1 (1)
EAc	1 (0.5)	1 (1)	1 (1)	1 (1)	3 (3)	2 (2)
FAv	0.5 (0.2)	1 (1)	0.5 (0.5)	0.3 (0.3)	1 (1)	1 (1)
FAc	0.5 (0.25)	1 (1)	1 (1)	0.5 (0.5)	1 (1)	1 (1)

Water availability emerged as the strongest-performing indicator; in contrast, food availability consistently recorded the lowest performance across both scales, indicating persistent concerns regarding affordability, distribution, and equitable resource access despite the agricultural significance of the region. The integrated WEF nexus composite index values of 0.185 for Mpumalanga Province and 0.210 for Ehlanzeni District Municipality indicate moderate sustainability according to the sustainability classification scale.

Table 3. A presentation of the normalised indices for the six WEF-related indicators generated using stakeholder pairwise comparison matrices at Mpumalanga Province and Ehlanzeni District scales.

Indicator	Mpumalanga Province	Ehlanzeni District Municipality
Water availability (WAv)	0.201	0.394
Water accessibility (WAc)	0.163	0.115
Energy availability (EAv)	0.180	0.134
Energy accessibility (EAc)	0.218	0.174
Food availability (FAv)	0.109	0.082
Food accessibility (FAc)	0.129	0.101
Integrated WEF nexus composite index	0.185	0.210

Spider diagrams illustrating the distribution of the normalised WEF indicators revealed uneven polygonal shapes across both scales, indicating sectoral imbalances and varying levels of resource security within the nexus at both scales (Figure 3). The imbalance in WEF resources management and security is more pronounced in Ehlanzeni District than Mpumalanga Province. These irregular profiles on WEF Nexus radar graphs are commonly interpreted as evidence of trade-offs and governance fragmentation in integrated resource systems (OECD, 2018).

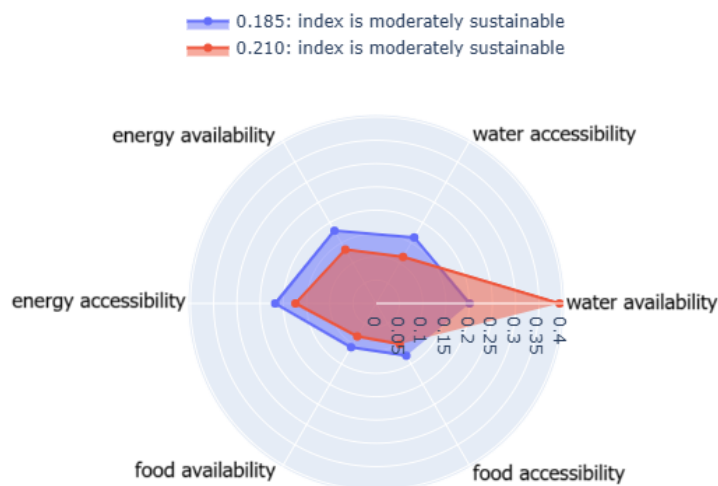


Figure 3. Comparative spider diagram illustrates the six normalised indices as relative performance of the six WEF-related indicators of the Mpumalanga province (blue) and the Ehlanzeni District (orange), derived using stakeholder-informed PCMs in the iWEF tool.

3. DISCUSSION

Water availability emerged as the strongest-performing indicator across both study areas, particularly within the Ehlanzeni District, reflecting stronger local infrastructure provision and institutional coordination within the Crocodile River Catchment. Similar patterns have been reported in sub-national WEF nexus studies across Southern Africa, where district-level assessments often outperform broader provincial evaluations (Nhamo et al., 2020). However, lower provincial scores suggest that rural and peripheral communities continue to experience water access and infrastructure challenges. Energy availability and accessibility emerged as key constraints across both spatial scales, affecting water treatment, irrigation, food processing, and agricultural productivity. These findings align with previous South African WEF nexus studies identifying energy insecurity as a major limitation to integrated resource sustainability and climate resilience (Khofi et al., 2025). Food availability and accessibility recorded the lowest performance despite the agricultural significance of the Crocodile River Catchment. This suggests that food insecurity is more strongly linked to affordability, socio-economic inequality, and distribution limitations than production shortages. Similar trends have been observed nationally, where the country South Africa and the province Mpumalanga remain food-sufficient overall but continues to experience household-level food insecurity (van den Berg & Walsh, 2023).

4. CONCLUSIONS

The findings highlight the importance of improving equitable resource access, strengthening resilience, and enhancing integrated resource governance to support long-term sustainability. The study further demonstrates the value of sub-national WEF nexus assessments for identifying sectoral trade-offs, governance fragmentation, and localised vulnerabilities that may be overlooked in broader provincial-scale evaluations.

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ASSESSING THE IMPACT OF WEF NEXUS STRATEGIES ON SMALLHOLDER FARMER'S PRODUCTIVITY IN AGRI-PARKS, GAUTENG PROVINCE, SOUTH AFRICA

Kwena Mpati^{1,2}, Aluwani Tagwi², and Sylvester Mpandeli³

ABSTRACT

Agricultural production in South Africa is increasingly constrained by climate variability, water scarcity, energy instability, and natural resource degradation, with smallholder farmers disproportionately affected due to limited infrastructure and fragmented institutional support. This study applies a Water-Energy-Food (WEF) nexus framework to examine how integrated resource management influences farm productivity and market access within the Sustainable Agri-parks model in Gauteng Province. A quantitative approach was employed using data from 148 smallholder farmers located within Agri-parks, those within a 30 km radius accessing Agri-park services, and nearby non-participating farmers. A composite WEF index was developed to measure the adoption of water management practices (including irrigation systems), energy use, and food production techniques. Regression analysis was used to assess the relationship between WEF adoption and farm productivity. Results show that farmers with access to Agri-park services achieved higher WEF adoption scores, particularly in water and energy practices. Drip irrigation emerged as the dominant water management practice, especially among larger, younger, and better-educated farmers, reflecting its role in improving water-use efficiency. Farm size and education significantly influenced adoption, while gender and age had limited effects. Higher WEF scores were positively associated with farm productivity in bivariate analysis; however, this relationship weakened after controlling for socio-economic and structural factors. Notably, access to Agri-park services remained a significant determinant of productivity, underscoring the importance of institutional support in enabling effective resource integration. The findings demonstrate that integrating irrigation, energy use, and sustainable agricultural practices enhances resource-use efficiency and supports improved productivity and market readiness. The study highlights the role of Agri-parks as institutional platforms that facilitate coordinated WEF implementation, particularly through improved irrigation management and access to services. Strengthening integrated resource planning, farmer capacity development, and infrastructure investment is critical for advancing sustainable smallholder agriculture in water-constrained environments. This study provides practical evidence for policymakers and practitioners on how integrated irrigation and WEF-based interventions can enhance smallholder resilience, productivity, and market participation in water-scarce, semi-arid environments.

Keywords: Water-Energy-Food (WEF) Nexus; irrigation; smallholder farmers; Agri-Parks; integrated resource management; agricultural productivity; South Africa.

1. INTRODUCTION

Global agricultural systems are increasingly constrained by climate variability, water scarcity, rising energy demand, and population growth, intensifying pressure on sustainable food production (Mondal et al., 2025). These challenges are particularly severe in developing regions where agriculture depends heavily on climate-sensitive natural resources, irrigation systems, and water management infrastructure. Smallholder farmers are disproportionately affected due to fragmented governance, inadequate

¹ City of Tshwane, Environment and Agriculture Management Department, Pretoria, South Africa); E-mail: Kwenamp@tshwane.gov.za

² College of Agriculture and Environmental Sciences, University of South Africa, Florida, South Africa.); E-mail: Tagwia@unisa.ac.za

³ Water Research Commission (WRC), Lynnwood Manor, Pretoria, South Africa); E-mail: Sylvesterm@wrc.org.za

infrastructure, weak institutional coordination, and limited access to finance and technology. In South Africa, these constraints are further reinforced by socio-economic inequalities and uneven agricultural development. Empirical evidence shows that systemic inefficiencies in governance, infrastructure, and resource management continue to restrict equitable resource access and agricultural performance (Khofi et al., 2025). Sectoral and silo-based management of water, energy, and food systems further constrains integrated resource planning across the Southern African Development Community, including South Africa (Nhamo et al., 2018). Institutional implementation challenges, weak coordination, and limited partnerships have also undermined agricultural and irrigation support programmes (Adom et al., 2022).

Although the Water-Energy-Food (WEF) nexus provides an integrated framework for improving water-use efficiency, irrigation sustainability, and resource-use optimisation, empirical evidence linking WEF adoption to farm-level productivity remains limited. The WEF nexus framework further creates an opportunity for the agricultural sector to adopt and build strong coping and adaptive strategies to deal with any natural vagaries. The agricultural sector is one of the climate-sensitive sectors, and it is expected that it should produce more food with fewer resources. By simultaneously addressing water management (e.g., irrigation efficiency), energy access (e.g., renewable-powered irrigation), and food production systems (e.g., diversified cropping), the WEF nexus offers pathways to improve resource-use efficiency and farm performance. Despite its conceptual relevance, empirical evidence linking the WEF nexus to smallholder productivity outcomes remains limited (Judijanto, 2025).

In South Africa, Agri-park initiatives provide a strategic platform for smallholder support through shared infrastructure, institutional coordination, and market integration (Maponya, 2021). Most studies rely on macro-level modelling or sectoral assessments, with insufficient attention to farm-scale behavioural adoption, irrigation performance, and productivity outcomes. Regional WEF assessments indicate marginal sustainability and systemic vulnerability in southern Africa (Mabhaudhi et al., 2019), yet these aggregated metrics provide limited insight into smallholder adaptive capacity and on-farm resource management practices. This gap underscores the need for empirical evaluation of integrated resource management within institutional agricultural platforms.

CONCEPTUAL FRAMEWORK: INTEGRATED WEF IN AN AGRI- PARK SYSTEM

As illustrated in Figure 1, the Water-Energy-Food (WEF) nexus framework conceptualises agricultural production within Agri-park systems as an integrated and interdependent structure, where water (irrigation practices), energy (sources and technologies), and food production (agronomic and management practices) function as interconnected components of a single system. Rather than treating these elements in isolation, the framework recognises that improvements in one domain, such as efficient irrigation, are dependent on energy access and directly influence food production outcomes. Within the Agri-park context, these interactions are operationalised through shared infrastructure, coordinated service delivery, and institutional support, which collectively enable the practical implementation of WEF strategies at the farm level. In this study, the conceptual framework is translated into an empirical analytical structure through the construction of a composite WEF index, which quantitatively captures the combined effects of water, energy, and food practices.

This allows for the assessment of both individual components and their integrated influence on farm productivity and market readiness. The framework further recognises that WEF outcomes are shaped by enabling conditions such as access to Agri-park services, farm size, and farmer capacity. This is reflected in the results, where higher WEF scores and improved productivity are observed among farmers with institutional support, while imbalances across components, particularly the lower performance of the food dimension, highlight gaps in achieving full integration. Thus, the conceptual framework not only guides the analysis but also provides a practical lens for understanding how coordinated water, energy, and food interventions can enhance resource-use efficiency, strengthen irrigation performance, and support sustainable smallholder agriculture in water-constrained environments.

2. METHODS

2.1 Study Area and Sampling

This study was conducted across multiple Agri-park sites in Gauteng Province, South Africa, including Rooiwal, Soshanguve, Tarlton, Westonaria, Rethabiseng, Sokhulumi, Tshwane Food and Energy Centre, Camel Estate, Sebokeng, and surrounding areas. The study area falls within a semi-arid region characterised by variable rainfall patterns and increasing water scarcity, where agricultural production is largely dependent on supplementary irrigation. Farmers utilise a mix of surface water, groundwater, and municipal water sources, with irrigation systems ranging from drip and sprinkler to manual methods. Farmers were stratified into three groups aligned with the study's core aim: (i) farmers actively operating within Agri-parks, (ii) those within a 30 km radius who accessed Agri-park services, and (iii) farmers in surrounding areas not participating in Agri-park activities. A stratified sampling approach was employed to ensure adequate representation across these groups. This design enabled the analysis of variations in resource-use practices across different levels of institutional support. The analytical framework was structured to capture cross-sectoral interactions among water, energy, and food variables, ensuring that WEF dynamics were assessed as an integrated system.

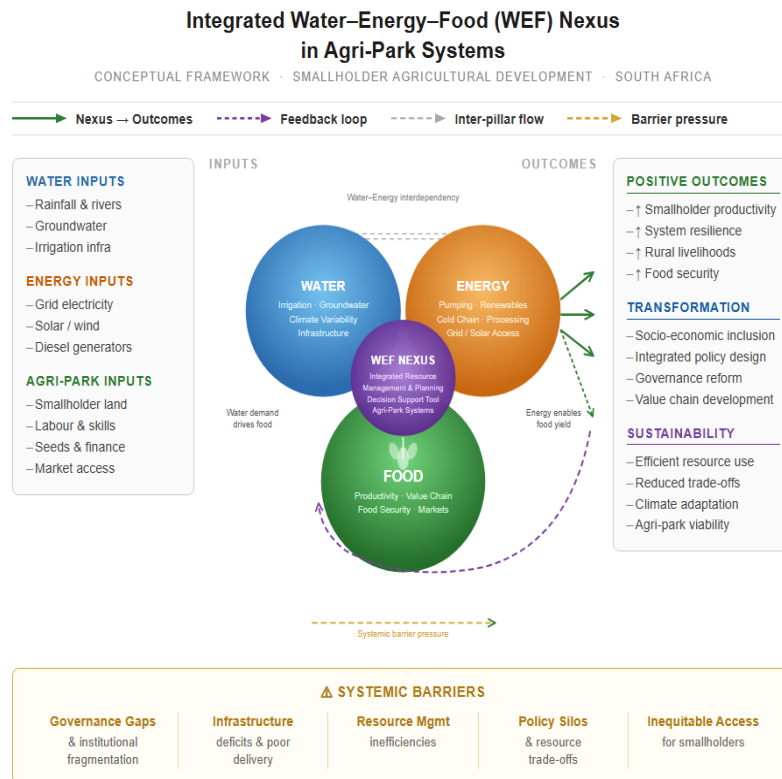


Figure 1: Integrated Water-Energy-Food (WEF) nexus conceptual framework for the Agri-park system. Source: Author (2026)

2.2 Data Collection

A mixed-methods approach was employed to triangulate findings. Structured surveys were administered to 148 smallholder farmers, capturing data on irrigation practices, energy use, food production, and socio-economic characteristics. The survey instrument included detailed modules on irrigation systems, water sources, irrigation frequency, water application methods, and access to irrigation infrastructure. Data on energy use for irrigation, including electricity, diesel, and renewable energy sources, were collected to assess irrigation energy linkages.

Food production data covered a range of agronomic and farm management practices, including soil fertility management (e.g., soil testing, use of manure/compost, and fertiliser application), crop management practices (e.g., crop rotation, intercropping, spacing, and timely weeding), pest and disease control (e.g., scouting, pesticide use, and biological control), and post-harvest handling. Additional information on seed use, mechanisation, and farm management practices was also collected. Ethical considerations were strictly observed. Informed consent was obtained from all participants, and anonymity and confidentiality were maintained throughout the study.

2.3 Analytical Framework

To assess integrated Water-Energy-Food (WEF) adoption, a composite WEF index was constructed to capture the extent of water-efficient irrigation practices, sustainable energy use, and improved food production practices at the farm level. The water component included irrigation methods, water management practices, and access to water sources, while the energy component reflected the type and source of energy used for irrigation and other farm operations. The food component incorporated agronomic practices such as soil fertility management, crop production techniques, pest and disease control, post-harvest handling, and mechanisation. For each component, exploratory factor analysis using the iterated principal factor method was applied to identify underlying adoption patterns, reduce measurement error, and combine multiple indicators into a single composite score. The factor analysis for each nexus component is defined as follows. Let a smallholder farmer i be characterised by observed indicators of Water, Energy, and Food systems collected in a vector:

$$\text{Water equations:} \quad W_i = \Lambda_W F_i + \varepsilon_W \quad (1)$$

$$\text{Energy equations:} \quad E_i = \Lambda_E F_i + \varepsilon_E \quad (2)$$

$$\text{Food equations:} \quad FP_i = \Lambda_F F_i + \varepsilon_F \quad (3)$$

Where,

- W_i = vector of water-related indicators.
- E_i = vector of energy-related indicators.
- FP_i = vector of food indicators.
- ε_i is the error term related to each component.

These three normalised components were then integrated through a second-stage factor analysis to produce the final WEF index, reflecting the overall level of integrated resource-use efficiency. The equation for this second-level factor analysis for the WEF index is presented below.

A combined WEF score can be expressed as:

$$WEF_i = \sum_{j=1}^m w_j F_{ji} \quad (4)$$

Agricultural productivity was measured as scaled gross value per hectare, serving as a proxy for farm performance under varying water, energy, and food management conditions. Quantitative analysis included descriptive statistics to summarise adoption patterns and ordinary least squares (OLS) regression to quantify the effect of WEF adoption on productivity while controlling for key socio-economic and farm-level characteristics, as presented below.

$$Y_i = \beta_0 + \beta_1 WEF_i + \gamma' Z_i + \varepsilon_i \quad (5)$$

where Y_i denotes the scaled crop value per hectare for the farmer i , WEF_i is the standardised Water-Energy-Food index, Z_i is a vector of control variables, and ε_i is the error term. All statistical analysis were conducted using IBM SPSS statistics. This approach ensures that the analytical framework captures both the integrated nature of the WEF nexus and the influence of institutional, structural, and

demographic factors on smallholder productivity, providing a robust, defensible basis for examining how combined water, energy, and food management practices impact farm performance and irrigation efficiency.

3. RESULTS AND DISCUSSION

3.1 WEF score and its components

The results from Table 1 demonstrate that adoption of the Water-Energy-Food (WEF) nexus among smallholder farmers in Gauteng remains uneven across its three components, with an overall WEF score of 30.6, reflecting moderate integration. Disaggregation of the index shows relatively stronger performance in energy (32.7) and water (30.2) compared to the substantially lower food score (16.1), highlighting a critical imbalance in the implementation of the nexus

$$(W_i = \Lambda_W F_i + \varepsilon_W; E_i = \Lambda_E F_i + \varepsilon_E; F_i = \Lambda_F F_i + \varepsilon_F). \quad (6)$$

Farmers with access to Agri-park services (refers to the extent to which farmers benefited from institutional, infrastructural, technical, and production support interventions provided through the Agri-park programme) achieved higher and more balanced WEF outcomes (33.9) than non-users (28.8), with improvements observed across water (33.7 vs 28.2), energy (34.8 vs 31.6), and food (17.1 vs 16.0) components. Similarly, farmers with matric-level education (secondary education completion/grade 12) or higher recorded significantly higher WEF scores (33.7) compared to those with lower education (26.0), while larger farms (>2 ha) achieved the highest WEF scores (34.5) relative to small-scale farms (<2 ha) (21.8), indicating the importance of both human and physical capital in enabling integrated adoption across all three domains. In contrast, gender and age differences were minimal, suggesting that WEF adoption is primarily shaped by structural and institutional factors rather than demographic characteristics.

Importantly, these descriptive findings align with the regression results, which indicate that although higher WEF scores are positively associated with farm productivity in the bivariate model, the relationship weakens after controlling for socio-economic and structural characteristics. This suggests that part of the observed association between WEF adoption and productivity may be explained by underlying factors such as institutional support, education level, and farm resource endowment, which simultaneously influence both WEF practice adoption and productivity outcomes.

This indicates that productivity gains are not driven by improvements in water (30.2), energy (32.7), or food (16.1) components in isolation, but rather by the extent to which these are implemented in an integrated and mutually reinforcing manner. Therefore, the WEF nexus in this context should be understood not simply as the aggregation of component scores, but as a system requiring balanced co-development across water, energy, and food. The findings underscore the need for policy and programme interventions, particularly through Agri-parks, to strengthen the underperforming food dimension while sustaining gains in water and energy, thereby advancing a more explicit, balanced, and operational WEF approach that can enhance productivity and market access sustainably.

Table 1. Water-, Energy-, Food-, and WEF- Scores by Farmer Characteristics.

		Water Score	Energy Score	Food Score	WEF score
Accessed Agri-park services	No	28.2	31.6	16.0	28.8
	Yes	33.7	34.8	17.1	33.9
Gender	Female	30.1	32.9	13.5	30.2
	Male	30.3	32.4	20.1	31.2
Education Level	Below matric	26.2	28.7	13.1	26.0
	Matric&above	32.8	35.3	18.1	33.7
Age group	Older(>35)	30.2	31.9	16.8	30.5
	Youth(<36)	30.3	35.4	13.5	31.2

		Water Score	Energy Score	Food Score	WEF score
City	City of Tshwane	30.2	31.7	19.0	30.8
	City of Johannesburg	30.2	33.5	13.7	30.5
Land size	small(<2 Ha)	22.2	27.5	7.1	21.8
	Large(>2Ha)	33.7	35.0	20.1	34.5
Overall	Total	30.2	32.7	16.1	30.6

3.2 Water Management practices and irrigation adoption

Within the Water-Energy-Food (WEF) nexus framework, water management practices are a key determinant of farm productivity, particularly when integrated with energy and food production strategies. As shown in Table 2, drip irrigation emerges as the most widely adopted method across farmer categories. Adoption is higher among farmers accessing Agri-park services (69% vs. 61%) and those with matric-level education or above (73% vs. 50%). Similarly, younger farmers under 36 years (71% vs. 62%) and those operating larger farms (>2 ha) (77% vs. 31%) demonstrate significantly higher uptake, indicating that both human capital and farm scale facilitate the adoption of efficient irrigation technologies. In contrast, manual irrigation remains more prevalent among resource-constrained farmers, particularly smallholders (<2 ha) (35%) and those with lower education levels (25%). Sprinkler irrigation is more common among small-scale farms (34%) and in the City of Tshwane (41%), although its adoption is lower among farmers with Agri-park support (14%), suggesting a shift towards more efficient systems such as drip irrigation where institutional support is available. Gender and age dynamics show that male and older farmers are more likely to operate without irrigation, whereas female and younger farmers demonstrate higher adoption of drip systems. Spatial differences are also evident, with farmers in Johannesburg favouring drip irrigation (74%), while those in Tshwane rely more on sprinkler systems (41%), reflecting variations in local water infrastructure and access conditions.

Table 2. Irrigation Method by Farmer Characteristics.

		No irrigation used	Manual irrigation	Sprinkler	Drip
Accessed Agri-park services	No	9%	12%	29%	61%
	Yes	10%	19%	14%	69%
Gender	Female	5%	13%	25%	66%
	Male	15%	17%	23%	60%
Education Level	Below matric	10%	25%	29%	50%
	Matric & above	9%	8%	21%	73%
Age group	Older(>35)	11%	14%	26%	62%
	Youth(<36)	4%	14%	18%	71%
City	City of Tshwane	12%	14%	41%	57%
	City of Johannesburg	11%	15%	17%	74%
Land size	small(<2 Ha)	8%	35%	34%	31%
	Large(>2Ha)	13%	7%	28%	77%

Beyond irrigation methods, smallholder farmers employ complementary water management practices to improve water-use efficiency. These include mulching (41%), maintenance of irrigation infrastructure (34%), use of shade nets (27%), water scheduling (13%), and solar-powered pumping (8%), as presented in Table 3. These practices demonstrate the integration of water and energy management strategies within farming systems, contributing to improved resource efficiency. Importantly, these water management practices, particularly the adoption of drip irrigation combined with energy-efficient technologies such as solar pumping and improved crop management, are associated with higher WEF scores. This reinforces the integrated nature of the WEF nexus, where coordinated improvements in water, energy, and food systems drive better outcomes. The findings highlight that institutional support

through Agri-parks, alongside farm size and education, plays a critical role in enabling the adoption of efficient and integrated water management practices. This, in turn, strengthens the capacity of smallholder farmers to improve productivity and enhances their readiness for market participation within water-constrained environments.

Table 3. Adoption of Water Management Practices by Access to Agri-Park Services.

Water Management Practices	No	Yes	Total
Sprinkler irrigation	29%	14%	22%
Use of drip irrigation	61%	69%	65%
Water scheduling	9%	19%	13%
Use of solar to pump water	10%	5%	8%
Mulching	51%	29%	41%
Use of shade nets	25%	29%	27%
Regular maintenance of irrigation infrastructure	26%	42%	34%

3.3 Impact of WEF-Enabled Practices on Farm Productivity

Table 4 presents the results of the ordinary least squares regression examining the relationship between the WEF nexus index and farm productivity, measured as the scaled gross value of crop output per hectare. Model 1 includes only the WEF index, while Model 2 adds socio-demographic and structural controls. In Model 1, the WEF index is positively associated with farm productivity and is statistically significant at the 10 percent level, indicating that higher WEF scores are correlated with higher levels of value-based productivity. This aligns with prior research indicating that integrated WEF practices can enhance farm performance by improving efficiency in water, energy, and food systems (Simpson et al., 2019). However, after considering access to Agri-park services, gender, education level, age group, and land size in Model 2, the coefficient on the WEF index decreases in magnitude and loses statistical significance, suggesting that the bivariate association is partly explained by other household and institutional characteristics.

Among the control variables included in Model 2, access to Agri-park services shows a positive and statistically significant association with farm productivity at the 5 percent level. Farmers who reported accessing Agri-park services exhibit higher gross value per hectare compared to those who did not access such services. This finding reinforces evidence that institutional support and coordinated service provision can play a key role in enhancing productivity in smallholder contexts (Mabhaudhi et al., 2018; Simpson et al., 2019). Other control variables, including gender of the household decision-maker, education level, youth status, and land size category, do not display statistically significant associations with productivity in this specification. The R-squared values indicate that Model 2 explains a greater share of the variation in farm productivity than Model 1, although overall explanatory power remains modest, which is consistent with the heterogeneous nature of smallholder production systems. Values in brackets for model1 & 2 represent standard errors.

Table 4. OLS Regression Results for the WEF Index and Farm Productivity.

	(1)	(2)
VARIABLES	Model 1	Model 2
WEF Nexus Index	0.203*	0.124
	(0.110)	(0.112)
Accessed Agri-park services: No(Ref)		8.007**
Accessed Agri-park services: Yes		(3.283)
Gender of Household head: Female		0.069
Gender of Household head: Male		(3.530)

VARIABLES	(1) Model 1	(2) Model 2
Education: Below matric (Ref)		1.025
Education: Matric & above		(3.266)
Age:36+		-2.432
Age: youth (<36)		(4.015)
Land size: Small (<2Ha Ref)		2.641
Land size: large (>2 Ha)		(3.319)
Constant	10.788*** (3.494)	7.525 (5.003)
Observations	132	132
R-squared	0.039	0.088

4. CONCLUSION

The study demonstrates that adoption of the Water-Energy-Food (WEF) nexus among smallholder farmers in Gauteng Agri-parks remains moderate and uneven across its components, with stronger performance in water and energy relative to the food dimension. This imbalance limits the full realisation of the nexus, as improvements in water and energy systems do not automatically translate into enhanced productivity without corresponding advancements in agronomic and production practices.

The findings further highlight that the effectiveness of the WEF nexus lies not in the adoption of individual components, but in their coordinated and simultaneous implementation. Integrated practices such as drip irrigation supported by reliable energy sources illustrate how water and energy systems interact to improve food production outcomes. However, the regression results indicate that these benefits are significantly influenced by institutional factors, with access to Agri-park services emerging as the most consistent determinant of productivity.

Importantly, the study demonstrates that integrated WEF adoption enhances not only farm productivity but also market readiness. Farmers with higher WEF scores and institutional support are better positioned to meet market requirements through improved production consistency, resource efficiency, and product quality. This underscores the role of Agri-parks as critical institutional platforms that facilitate both resource integration and market participation.

For policy and practice, the findings suggest that strengthening the WEF nexus requires a shift from sectoral interventions towards coordinated and system-based approaches. Investments in irrigation efficiency must be complemented by energy access and improved agronomic practices, supported by institutional frameworks that enable smallholder farmers to adopt and sustain integrated solutions. Enhancing farmer capacity, expanding access to renewable energy technologies, and strengthening Agri-park governance structures are therefore essential for achieving sustainable productivity and inclusive market participation in water-constrained environments.

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QUANTIFYING WATER–ENERGY–FOOD (WEF) NEXUS IN SOUTHERN IRAQ THROUGH CLIMATE-SMART AGRICULTURE AND FARMER FIELD SCHOOLS

Amani Alfarra^{1*}, Muhammad Munir¹, Sami Ouechtati¹, and Waleed H. Abouelhassan¹

ABSTRACT

Southern Iraq's irrigated wheat production systems face increasing Water–Energy–Food (WEF) pressures driven by water scarcity, salinity stress, and high irrigation energy costs. This paper presents a field-based case study that operationalizes the WEF nexus through a Farmer Field School (FFS) delivery approach model combined with a Climate-Smart Agriculture (CSA) technology package implemented by the Food and Agriculture Organization of the United Nations (FAO) with funding from Global Affairs Canada (GAC) and Swedish International Development Cooperation Agency (SIDA).

During the 2024–2025 winter wheat season, 21 FFS demonstration plots applying CSA practices, i.e., Laser Land Levelling (LLL), climate-resilient seed, precision sowing, improved nutrient management, and optimized irrigation, were established alongside adjacent traditional farmer plots across six governorates (Maysan, Dhi Qar, Wasit, Babil, Najaf, and Muthanna).

The intervention design integrated water efficiency, energy saving and food production objectives to operationalize WEF nexus interaction at field level. A mixed method approach combining field measurements, farmers feedback and economic analysis was applied to assess both food production performance and socioeconomic outcomes, including farmers adoption potentials, cost effectiveness and risk reduction.

Results indicate strong WEF nexus performance under the intervention package of Laser Land Levelling and associated CSA practices reduced irrigation time and applied water by approximately 33%, reduced diesel fuel consumption for pumping by 44%, and increased wheat yield by an average of 58% across six governorates. This resulted in an increase by a factor of 2.35 increase in relative water productivity, meaning farmers now produce more than twice the wheat with the same amount of water, demonstrating significant gains in water-use efficiency and productivity.

Economic performance was strong with incremental Cost/Benefit Ratio, CBRs (revenue from yield gains divided by the costs) ranging from 2.07 to 5.94 (mean 3.77), indicating high adoption potential, improved incomes and reduced vulnerability to climate shocks. Ecosystem co-benefits include possible lower risks of waterlogging and soil salinization due to improved land and water management.

The findings show that the FFS–CSA model provides a scalable framework for operationalizing the WEF nexus, informing policy, extension, and investment decisions while advancing SDGs on water efficiency, food security, clean energy, and climate resilience. While the findings are based on operational field comparisons rather than randomized experimental trials, the results provide strong indicative evidence of the potential WEF benefits of integrated CSA interventions in southern Iraq.

Keywords: Water-Energy-Food (WEF) Nexus, Climate Smart Agriculture (CSA), Farmers Field Schools (FFS), Laser Land Levelling (LLL), Water Productivity, Energy Efficiency, Wheat Production, Irrigation Efficiency, Cost Benefit Ratio (CBR), Climate Resilience

¹ Land and Water Officer, Food and Agriculture Organization of the United Nations (FAO), Viale delle Terme di Caracalla, 00153 Rome, Italy.

* Email: amani.alfarra@fao.org

1. INTRODUCTION

Southern Iraq's irrigated wheat systems sit at the intersection of acute water scarcity, costly irrigation energy, and fragile agro-ecosystems conditions that amplify Water–Energy–Food (WEF) trade-offs and make multi-benefit interventions especially valuable. Agriculture dominates freshwater withdrawals in Iraq, accounting for approximately 79% of annual withdrawals (World Bank 2022), which increases the development value of verified water productivity gains.

A WEF nexus approach recognises that decisions in irrigation and agriculture shift energy demand and ecosystem outcomes, and that integrated appraisal reveals synergies as well as trade-offs. FAO's nexus framing stresses that management should handle competing resource interests 'while ensuring the integrity of ecosystems' (FAO 2014a, 2014b). World Bank reporting (World Bank 2021) links drought and water or electricity shortages to widespread disruption in agriculture, projects that Iraq's per-capita freshwater availability will approach the 1,000 m³/person/year scarcity threshold by 2035 under business-as-usual conditions and estimates that a 20% reduction in water supply could reduce real GDP by up to 4%.

The Ecosystems pillar is operationally critical in southern Iraq. UNEP (2023) describes the Ahwar / Mesopotamian marshlands as facing severe ecological stress from drought, upstream dam construction, over-abstraction, extreme heat, and wastewater contamination, reinforcing the importance of interventions that reduce irrigation-driven water depletion and salinity stress at the basin scale.

Despite increasing policy attention to the WEF nexus, limited empirical evidence exists from field-level agricultural interventions in fragile and water-scarce environments such as southern Iraq. In particular, quantitative assessments linking Climate-Smart Agriculture (CSA), Farmer Field Schools (FFS), and measurable WEF nexus outcomes remain limited. This study addresses this gap by assessing the combined water, energy, food production, economic, and ecosystem implications of a combined CSA intervention implemented through FFS approach.

While water, energy, food production, and economic outcomes were directly assessed through field measurements and economic analysis, ecosystem benefits were evaluated indirectly through established relationships between improved land and water management, reduced waterlogging, lower salinity risks, and reduced pressure on water resources.

This paper presents quantitative WEF results from an FAO Farmer Field School (FFS), Climate-Smart Agriculture (CSA) intervention implemented across six governorates of southern Iraq during the 2024, 2025 winter wheat season. It derives a set of ICID-aligned nexus metrics, including energy and CO₂e savings, relative water and energy productivity indices, a CBR summary statistic, and a composite WEF synergy index, grounded in published conversion factors (EIA 2023; NZ MfE 2024; GHG Protocol 2023) to demonstrate multi-sector performance at field scale.

The objective of this study is to quantify the WEF nexus in response to the integrated CSA practices implemented through Farmer Field Schools in southern Iraq's irrigated wheat production systems.

2. STUDY AREA AND METHODOLOGY

2.1 Study Area and WEF Context

The intervention covered six governorates of southern Iraq: Maysan, Dhi Qar, Wasit, Babil, Najaf, and Muthanna—flat alluvial plains with gravity-fed and pump-lift canal irrigation, salinity-affected soils, and wheat as the dominant winter crop. The detailed WEF assessment was conducted using representative wheat FFS plots selected to demonstrate dominant production conditions within each governorate. Although the sample size limits statistical generalization, the approach was considered appropriate for operational field validation and demonstration-based learning contexts. A seventh governorate, Diwaniyah, was excluded from analysis due to complete crop failure from extreme water scarcity and

volatile canal releases at critical growth stages (FAO Iraq 2025, pp. 1–2). This exclusion is itself a WEF insight: field-level efficiency gains can be overwhelmed by systemic allocation volatility a governance constraint the technology package alone cannot resolve (World Bank 2021).

2.2 *Intervention Package: FFS + CSA*

FAO defines CSA as an approach seeking to sustainably increase productivity and incomes, strengthen adaptation and resilience, and reduce greenhouse gas emissions where possible (FAO 2013). The intervention delivered a bundled CSA technology package through a season-long Farmer Field School (FFS) model; where farmers observe and compare demonstration and traditional plots under facilitation (FAO 2023) - comprising:

- Laser Land Levelling (LLL): GPS guided precision levelling to improve field micro-topography, promoting uniform water distribution, reducing over-irrigation in topographic lows, and lowering waterlogging and salinisation risk (FAO Iraq 2025).
- Climate-resilient wheat varieties: improved seed with higher yield potential and tolerance to salinity and drought stress (FAO Iraq 2025).
- Precision sowing using seed-cum-fertiliser drills: improved crop establishment and balanced input placement, increasing germination uniformity and input-use efficiency (FAO Iraq 2025, p. 4).
- Improved nutrient management: split-application NPK and foliar fertigation aligned with crop development stages (FAO Iraq 2025).
- Optimised irrigation scheduling: farmer-guided irrigation timing matched to crop demand rather than fixed-interval traditional practice (FAO Iraq 2025).
- The FFS model reduced early resistance to behavioural change once farmers observed water savings and yield improvements firsthand in adjacent plots (FAO Iraq 2025). Evidence from systematic review indicates that FFS effects depend strongly on facilitation quality and hands-on comparison logic (Waddington et al. 2014).

2.3 *Experimental Design and Data Collection*

Twenty-one wheat FFS plots were established alongside adjacent traditional practice comparator plots, with five to seven field-based training sessions at key growth stages. Twenty of 21 plots were assessed; one representative plot per governorate (5 donums = 1.25 ha) was selected for detailed WEF evaluation (FAO Iraq 2025). Monitoring combined: (i) quantitative field measurements of crop yield, irrigation time, and diesel fuel consumption per irrigation operation; (ii) structured farmer interviews mid-season (December 2024) and post-harvest (April 2025); and (iii) incremental cost–benefit ratio (CBR) analysis², calculated as incremental revenue from yield gains divided by incremental costs of LLL service, improved seed, and precision sowing equipment.

The study compares FFS demonstration plots with adjacent farmer-managed conventional plots rather than using a randomized experimental design. This approach is appropriate for practical farmer learning and operational field validation under real production conditions. The observed differences between FFS and conventional plots therefore provide strong indicative evidence of WEF benefits, however, they should not be interpreted as statistically controlled experimental estimates.

² CBR was calculated as total incremental benefits divided by total incremental costs (CBR = Benefits / Costs)

3. RESULTS MAPPED TO WEF ELEMENTS

3.1 *Water element*

LLL combined with optimised irrigation scheduling reduced irrigation time and applied water by approximately 33% across all six reporting governorates. A farmer testimony in the annex indicates that laser land levelling reduced irrigation time and water consumption by about one third (FAO Iraq 2025) which is consistent with the technical function of laser land levelling in terms of improving field uniformity and enabling more even water distribution, thus reducing excess water use and irrigation frequency. This aligns with peer-reviewed evidence from South Asian rice; wheat systems, where Ali et al. (2018) report that LLL adoption positively impacts irrigation water savings, crop yields, and household income, and highlight the role of service providers and institutional support in scaling.

In WEF terms, the 33% reduction in applied water implies higher water productivity where yields are maintained or increased. Reduced over-irrigation also lowers waterlogging frequency and slows secondary salinisation. The benefits are specifically important in Southern Iraq, where salinity and water scarcity are major environmental challenges faced by the farmers. Therefore, improved water management can help the farmers reduce pressure on agricultural lands and may indirectly benefit sensitive ecosystem such as the Ahwar Marshlands in Southern Iraq (FAO Iraq 2025; UNEP 2023). It should be noted that ecosystem outcomes were not directly measured through indicators such as soil salinity dynamics, groundwater responses, biodiversity status, or wetland condition. Rather, ecosystem co-benefits are inferred from the well-established effects of reduced over-irrigation, improved field drainage conditions, and lower agricultural water withdrawals, which are expected to contribute positively to soil health and broader ecosystem resilience in water-stressed environments.

3.2 *The Food element of the WEF-Nexus*

Table 1 shows wheat yield under CSA and traditional farmer plots across the six reporting governorates. Average wheat yield increased by 58%, ranging from 28.2% in Najaf to 80.0% in Dhi Qar. These gains substantially exceed the 13% average yield improvement reported in the Campbell systematic review of FFS interventions (Waddington et al. 2014), suggesting that the bundled CSA technology package—particularly laser land levelling as the primary physical intervention contributed substantially beyond FFS knowledge transfer alone.

3.3 *The Energy element of the WEF-Nexus*

Diesel fuel consumption for irrigation pumping declined across all six reporting governorates. The Wasit governorate provides the most concrete field example: fuel use dropped from 75 litres to 42 litres per irrigation operation, a reduction of 33 litres (44%) (FAO Iraq 2025), as reflected in the energy-saving indicators summarized in Table 2 and the derived calculations presented in Table 3. Another farmer testimony confirms that fuel consumption for pumping declined by the same one-third percentage as irrigation time (FAO Iraq 2025), reinforcing the Water & Energy coupling mechanism at the heart of the WEF nexus in diesel-dependent pump-lift systems (FAO 2014b). The corresponding energy savings, diesel energy equivalent, and avoided CO₂e emissions are summarized in Table 3.

3.4 *Economic Analysis*

Table 4 presents incremental CBRs ranging from 2.07 (Muthanna) to 5.94 (Dhi Qar) across the six reporting governorates (FAO Iraq 2025). These strong returns, driven jointly by higher yields, lower pumping fuel costs, and improved crop quality, indicate high adoption potential and reduced vulnerability to climate and price shocks. High CBRs also justify investment in LLL mechanisation-service delivery models, consistent with published recommendations for LLL scaling through public–private partnerships (Ali et al. 2018).

Table 1. Wheat yield comparison between CSA demonstration plots and traditional farmer plots across six governorates (2024–2025 winter wheat season)

Governorate	Yield (CSA) (Kg)	Yield (Traditional Farmers plot) (kg)	% Yield Increase of CSA over Traditional Plot
Maysan	1525	1015	50.2 %
Dhi Qar	1125	625	80 %
Wasit	1769	1080	63 %
Babil	1525	1015	50.2
Najaf	1364	1064	28.2 %
Muthanna	1004	607	65.4 %

Table 2. WEF nexus performance indicators by governorate for the southern Iraq wheat FFS–CSA intervention (2024–2025 winter wheat season)

Governorate	Yield Increase (%)	Water Saved (%)	Energy Saved (%)	CBR	Relative WP Index	Relative EP Index
Maysan	+50.2	33	44	3.23	2.36	2.82
Dhi Qar	+80.0	33	44	5.94	2.36	2.82
Wasit	+63.0	33	44	5.46	2.36	2.82
Babil	+50.2	33	44	3.03	2.36	2.82
Najaf	+28.2	33	44	2.90	2.36	2.82
Muthanna	+65.4	33	44	2.07	2.36	2.82
	+58.0	33	44	3.77	2.36	2.82

Note: WP = Water Productivity; EP = Energy Productivity; CBR = incremental Cost–Benefit Ratio. Water and energy savings for all governorates use headline values from FAO Iraq (2025); Wasit fuel data are directly reported. Relative WP and EP indices are derived from Eqs. (4) and (5) using average yield and water/fuel factors.

Table 3. Summary of derived energy, emissions, productivity, and composite WEF performance metrics (Wasit example and study-wide mean values)

Metric	Value	Source / Basis
Fuel saved (Wasit)	33 L per operation	FAO Iraq (2025) 75 – 42 L
Diesel energy content (ε)	38.29 MJ/L	EIA (2023) — 137,381 Btu/gal
Energy saved per operation	1,264 MJ (1.26 GJ)	33 × 38.29 MJ/L — Eq. (1)
CO ₂ e emission factor (EF)	2.68 kg CO ₂ e/L	NZ MfE (2024) mineral diesel
CO ₂ e avoided per operation	88 kg CO ₂ e	33 × 2.68 kg/L — Eq. (2)
CBR arithmetic mean	3.77	Eq. (3); FAO Iraq (2025)
Relative WP index (WP _{rel})	2.36 (+136%)	Eq. (4): 1.58 ÷ 0.67
Relative EP index (EP _{rel})	2.82 (+182%)	Eq. (5): 1.58 ÷ 0.56
WEF Index (S)	45 %	Eq. (6): (58+33+44)+3

Sources: FAO Iraq (2025, pp. 6, 9, 14); EIA (2023); NZ MfE (2024); GHG Protocol (2023). CO₂e values are Scope 1 direct combustion only. Relative WP and EP indices use average yield factor combined with site-specific or headline water/fuel factors as described in Eqs. (4)–(5).

Table 4. Summary of Cost–Benefit Ratio (CBR) Across Six Governorates.

Governorate	Benefits (ID / USD)	Costs (ID / USD)	Cost-Benefit-Ratio (CBR) (%)
Maysan	350,850 (≈ 242 USD)	108,500 (≈ 75 USD)	3.23
Dhi Qar	347,650 (≈ 240 USD)	58,500 (≈ 40 USD)	5.94
Wasit	483,370 (≈ 333 USD)	88,500 (≈ 61 USD)	5.46
Babil	353,550 (≈ 244 USD)	116,500 (≈ 80 USD)	3.03
Najaf	213,000 (≈ 147 USD)	73,500 (≈ 51 USD)	2.90
Muthanna	278,060 (≈ 192 USD)	134,500 (≈ 93 USD)	2.07

Source: CBR Calculation sheet (1 USD=1450 IQD)

3.5. Derived Calculations And Wef Metrics

This section provides transparent, step-by-step derivation of nexus indicators. Where seasonal totals are unavailable (e.g., total irrigation cycles per season), calculations are presented per Energy and CO₂e from Fuel Savings (Equations 1–2)

The Wasit fuel reduction of 33 L per irrigation operation (from 75 to 42 L; FAO Iraq 2025) is converted to energy saved (E_{saved}) using the U.S. Energy Information Administration diesel energy content factor $\epsilon = 38.29$ MJ/L, derived from EIA's reported 137,381 Btu per US gallon (EIA 2023):

$$E_{\text{saved}} = \Delta \text{Fuel} \times \epsilon_{\text{diesel}} = 33 \text{ L} \times 38.29 \text{ MJ/L} = 1,264 \text{ MJ} \text{ (1.26 GJ) per operation} \quad (1)$$

CO₂e avoided per operation ($\text{CO}_{2\text{e}_{\text{avoided}}}$) uses the mineral diesel emission factor $\text{EF} = 2.68$ kg CO₂e/L from the New Zealand Ministry for the Environment (NZ MfE 2024):

$$\text{CO}_{2\text{e}_{\text{avoided}}} = \Delta \text{Fuel} \times \text{EF}_{\text{diesel}} = 33 \text{ L} \times 2.68 \text{ kg CO}_{2\text{e}}/\text{L} = 88 \text{ kg CO}_{2\text{e}} \text{ per operation} \quad (2)$$

These estimates include only the direct emissions generated from diesel use during irrigation and do not account for indirect emissions related to fuel production and transport, consistent with GHG Protocol (2023). Seasonal energy savings and CO₂e reductions can be estimated by multiplying the per-irrigation values in Eqs. (1) and (2) by the total number of irrigation events in the season, once these data are available.

3.6 CBR Summary Statistics (Equation 3)

Using the six governorate CBR values in table 4 (FAO Iraq 2025), the arithmetic mean CBR is:

$$\text{CBR}_{\text{mean}} = (3.23 + 5.94 + 5.46 + 3.03 + 2.90 + 2.07) \div 6 = 22.63 \div 6 = 3.77 \quad (3)$$

Average benefits were approximately 3.8 times higher than average costs across the six reporting governorates (unweighted mean; FAO Iraq 2025), indicating a strong economic return from laser land levelling (LLL). This level of return suggests that LLL service provision can be commercially sustainable without long-term subsidies and could be incorporated into national agricultural extension programs and climate finance mechanisms, including Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) under the UNFCCC (FAO 2013).

3.7 Relative Water and Energy Productivity Indices (Equations 4–5)

Because absolute irrigation volumes and seasonal pumping totals are not reported, relative productivity indices are the only way to describe WEF performance. Let Y_1/Y_0 be the yield ratio, W_1/W_0 the water use ratio, and F_1/F_0 the fuel use ratio.

The ratios used in the WEF analysis were derived from project monitoring data: $Y_1/Y_0 = 1.58$, corresponding to a 58% increase in yield; $W_1/W_0 = 0.67$, corresponding to a 33% reduction in irrigation water use; and $F_1/F_0 = 0.56$, corresponding to a 44% reduction in fuel consumption based on the Wasit field data.

Where

- Y_1 = Yield in intervention plot (FFS–CSA plot)
- Y_0 = Yield in conventional farmer plot
- W_1 = Water used in intervention plot
- W_0 = Water used in conventional farmer plot
- F_1 = Fuel consumption in intervention plot
- F_0 = Fuel consumption in conventional farmer plot

Relative Water Productivity Index (WP_{rel}):

$$WP_{rel} = (Y_1/Y_0) \div (W_1/W_0) = 1.58 \div 0.67 = 2.36 (+136\% \text{ improvement over traditional practice})$$

(4)

Relative Energy Productivity Index (EP_{rel}):

$$EP_{rel} = (Y_1/Y_0) \div (F_1/F_0) = 1.58 \div 0.56 = 2.82 (+182\% \text{ improvement over traditional practice})$$

(5)

$WP_{rel} = 2.36$ means that FFS–CSA plots produced approximately 2.36 times more wheat per unit of applied water compared with traditional plots, consistent with the 2.35-fold gain reported in the field (FAO Iraq 2025, p. 6). $EP_{rel} = 2.82$ indicates that wheat output per unit of pumping fuel improved by 182% under the Wasit fuel example and headline yield gain. These are indicative composite indices; they should be presented as such unless verified with harmonised measurements across all sites.

3.7.1 WEF Index (Equation 6)

A simple WEF index S averages percentage improvements across the three measurable WEF dimensions (yield, water savings, energy savings) to express overall multi-sector convergence in a single indicator (FAO 2014b):

$$S = (\Delta Y\% + \Delta W\% + \Delta E\%) \div 3$$

(6)

Substituting mean observed improvement from FAO Iraq field data,

- $\Delta Y\% = 58$, $\Delta W\% = 33$, $\Delta E\% = 44$:
- $S = (58 + 33 + 44) \div 3 = 135 \div 3 = 45$

The resulting WEF index (S) is 45, representing the arithmetic mean percentage improvement across the three measured WEF elements: yield increase, water saving, and energy saving. In practical terms, this indicates that the intervention generated an average improvement of 45% across the three nexus elements. Because improvements are positive across all three elements and of comparable magnitude, the intervention demonstrates broad multi-sector benefits rather than gains concentrated in a single element.

4. DISCUSSION

4.1 *Interpreting the WEF Index*

The simultaneous achievement of lower water use, lower energy consumption, and higher food production demonstrates the practical WEF nexus impact of the CSA package. This directly reduces pumping time, fuel consumption, and associated CO₂e emissions while simultaneously enabling more uniform crop establishment and nutrient distribution. Improved seed varieties and precision sowing amplify the yield response by increasing crop yield under the more favourable water and nutrient regime. The magnitude of yield gains (58%) substantially exceeds the 13% average documented for FFS-alone interventions (Waddington et al. 2014), confirming that bundled technology package (laser land levelling, climate resilient wheat variety, precision cultivation method, improved nutrient management, and crop need based irrigation scheduling especially at critical crop growth stages such as root initiation, tillering stage, stem elongation, heading, anthesis, and grain filling) drives the majority of the gain; the FFS model's contribution is accelerating adaptation by reducing first-season risk through visible, side-by-side field evidence.

The average Cost Benefit Ratio (CBR) of 3.77 (Eq.3) indicates return on the intervention significantly exceeding the additional costs, showing a strong potential for farmers adoption. The profitability is also convincing in terms of laser land levelling service provision could become commercially viable with limited external support. If supported through appropriate policies and extension services, the FFS CSA model could effectively contribute to broader national commitments on agriculture modernization, water use efficiency and climate adoption in line with FAO's Climate Smart Agriculture framework (FAO 2013).

4.2 *Limitations and Uncertainties*

Several limitations constrain interpretation. First, the evaluation uses adjacent traditional plots rather than randomised assignment; confounding from unobserved differences in soil quality, farmer skill, or irrigation access cannot be ruled out. Second, water savings are reported as irrigation time reductions and farmer testimony rather than metered volumes (m³), precluding calculation of absolute water productivity (kg/m³). World Bank analysis (World Bank 2021) cautions that claims of water savings based only on withdrawal changes can be misleading if return flows and allocation rules are not assessed. Reporting should therefore describe 'reduced irrigation time and applied water' rather than 'water savings' unless consumptive use is quantified. Third, the Wasit fuel example covers one governorate and one operation; seasonal pumping totals were not reported, limiting extrapolation to annual energy and CO₂e savings. Fourth, the Diwaniyah crop failure demonstrates that field-level efficiency gains are bounded by systemic water allocation volatility (World Bank 2021; FAO Iraq 2025).

4.3 *Scaling Recommendations*

Three institutional input are critical for scaling. First, LLL access: Ali et al. (2018) showed that LLL outcomes depend on reliable service provision, equipment availability, calibration, maintenance, and fair pricing, making investment in LLL service markets and public-private partnerships essential. Second, FFS quality assurance: Waddington et al. (2014) found that large-scale FFS programmes can underperform when facilitator training quality deteriorates; phased expansion with maintained facilitator standards and cluster-based monitoring is recommended. Third, water governance integration: the Diwaniyah exclusion underscores the need to pair on-farm efficiency with predictable water allocation and drought contingency protocols at critical crop growth stages (World Bank 2021). Making the Ecosystems pillar explicit through monitoring of soil electrical conductivity, waterlogging incidence, and basin-level water balance effects, is also recommended, given UNEP's (2023) documentation of severe wetland stress in southern Iraq.

Beyond farm-level benefits, the findings have important implications for agricultural water management and climate adaptation policies in Iraq. The demonstrated combination of improved water productivity, reduced irrigation energy requirements, higher yields, and strong economic returns supports ongoing national efforts to modernize irrigation systems, increase agricultural water-use efficiency, and

strengthen climate resilience in the agricultural sector. The results suggest that integrating Laser Land Levelling and other Climate-Smart Agriculture practices into extension programmes, irrigation modernization initiatives, and farmer capacity development schemes could generate substantial resource-efficiency gains while contributing to national objectives related to food security, water conservation, and rehabilitation and salinity management, greenhouse gas emission reduction, and climate adaptation. The Farmer Field School approach further provides an effective mechanism for accelerating technology adoption and translating policy priorities into measurable field-level outcomes.

CONCLUSIONS

This study provides field-scale quantitative evidence that an integrated FFS–CSA intervention based on Laser Land Levelling, climate-resilient varieties, and precision sowing, delivers simultaneous, measurable WEF nexus gains across six governorates of southern Iraq. Key conclusions are:

1. Water: 33% reduction in irrigation time and applied water through LLL-driven field uniformity improvements, yielding a relative water productivity index WP_{rel} 2.36 (+136%) (Eq. 4).
2. Energy: 44% reduction in diesel fuel per irrigation operation (Wasit: from 75 to 42 L), corresponding to 1,264 MJ and 88 kg CO₂e emission avoided per operation (Eqs. 1–2), and EP_{rel} 2.82 (+182%) (Eq. 5).
3. Food: 58% average wheat yield increase, consistent across all six governorates (range 28.2% to 80.0%).
4. Economics: Mean CBR 3.77 (Eq. 3; range 2.07 to 5.94), supporting farmer adoption.
5. Composite nexus performance: WEF Index $S = 45$ (Eq. 6; Table 3), indicating balanced multi-sector improvement.
6. Ecosystem co-benefits: possible (unproven) reductions in waterlogging and soil salinisation risk from improved levelling and irrigation distribution (FAO Iraq 2025; UNEP 2023).

Strengthening this framework requires measured water uses for absolute productivity indicators, seasonal fuel records for annualised energy accounting, LLL service market development, and integration with water governance systems. The FFS–CSA model directly supports SDG 2 (food security), SDG 6 (water efficiency), SDG 7 (clean energy), and SDG 13 (climate action), and is well positioned to contribute to Iraq's nationally determined contributions and national adaptation plans (FAO 2013; World Bank 2021).

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WATER–ENERGY-FOOD-NUTRITION NEXUS FOR CLIMATE-RESILIENT DRYLAND FOOD SYSTEMS IN MENA AND SUB-SAHARAN AFRICA: AN INTEGRATED ANALYTICAL FRAMEWORK

Krishna Prasad Devkota^{1*}, Vinay Nangia¹, and Mina Devkota¹

ABSTRACT

Dryland food systems in Middle East and North Africa (MENA) and Sub-Saharan Africa (SSA) face intersecting pressures from water scarcity, energy poverty, and nutritional inadequacy. Northern Africa records critical agricultural water stress exceeding 121% of renewable freshwater resources; 67% of rural households in SSA dryland countries have no access to electricity; and Africa's dietary energy supply of 2,556 kcal/capita/day in 2023 remained 460 kcal below the global average. This paper develops a Water–Energy-Food-Nutrition (WEFN) Nexus framework integrating five data modules across 36 countries (18 MENA, 18 SSA) and 20 crops, giving equal analytical weight to all three Nexus elements. Nutritional water productivity (NWP) analysis demonstrates that pulses deliver 3.77 times more protein per cubic meter of water (324 vs. 86 g m⁻³) and 42–54% lower total use energy than irrigated rice, while dryland cereals such as pearl millet (7,560 kcal m⁻³) provide more than five times the caloric water productivity of rice (1,440 kcal m⁻³). Integrated good agronomic practices, conservation agriculture, biological N fixation, deficit irrigation, solar drip, seed system development, and frontier breeding science amplify neglected and underutilized species (NUS) performance across water–energy–soil nexus elements. The WEFN Nutrition Resilience Index (WEFN-NRI) identifies three vulnerability clusters across 36 countries. Scenario modelling projected for 2030 indicates that a diversified and renewable energy (DRE) scenario could reduce agricultural water stress by 50%, increase diet diversity by 67%, lower cereal import dependence by 45 percentage points, raise renewable irrigation energy by 45%, and improve WEFN-NRI by 55%, indicating a potential triple win across Nexus dimensions.

Keywords: water–energy-food-nutrition Nexus; nutritional water productivity; dietary energy supply; conservation agriculture; seed systems; MENA; Sub-Saharan Africa;

1. INTRODUCTION

The Water–Energy–Food (WEF) Nexus provides a central framework for managing resource interdependencies in food production systems (Bazilian et al., 2011; Hoff, 2011). However, in the dryland regions of MENA and SSA, where water scarcity, energy poverty, and food insecurity are most acute, WEF implementation remains constrained by an analytical imbalance. Water and energy are commonly quantified at system scale, whereas food is often represented only as aggregate crop yield rather than dietary energy, protein supply, or nutritional quality (Albrecht et al., 2018; Borgomeo et al., 2018). This mismatch creates important policy blind spots in regions where dietary inadequacy is severe and crop-portfolio decisions have major cross-dimensional Nexus implications.

Northern Africa's water stress exceeding 121% of renewable resources, 565 million people in SSA without electricity, more than 512 million projected to face chronic undernourishment by 2030 and 60% will be in Africa (UNICEF, 2023), and the limited availability of formal seed systems for neglected and underutilized species (NUS) crops (Devkota et al., 2025). In addition, there is no operational framework to quantify water, energy, and dietary elements across MENA and SSA with equal analytical weight. This paper addresses this gap through a Water–Energy-Food-Nutrition– (WEFN) Nexus that integrates five data modules across 36 countries. In this paper, it is hypothesized that dietary diversification towards pulses, cereals, and neglected and underutilized species (NUS) can support a WEF triple win by

¹ International Center for Agricultural Research in the Dry Areas (ICARDA), Morocco [*k.devkota@cgiar.org](mailto:k.devkota@cgiar.org)

reducing water stress, lowering energy use intensity, and improving nutritional adequacy, with further gains possible through agronomic, seed system, and scientific technology investments. This directly supports the ICID WEF-Nexus Working Group's mandate for integrated, evidence-based WEF policy.

2. MATERIALS AND METHODS

2.1 Countries coverage and crops scope

The analysis covers 18 MENA countries (Morocco, Algeria, Tunisia, Libya, Egypt, Jordan, Lebanon, Syria, Iraq, Yemen, Saudi Arabia, Oman, UAE, Qatar, Bahrain, Kuwait, Iran, Sudan) and 18 SSA dryland countries (Ethiopia, Eritrea, Somalia, Kenya, Tanzania, Chad, Niger, Mali, Burkina Faso, Senegal, Mauritania, Nigeria, Djibouti, Botswana, Namibia, Zimbabwe, Zambia, South Africa). Crops analysis covers 20 food crops: strategic staples (wheat, rice, maize); dryland-adapted cereals (barley, sorghum, pearl millet, finger millet, teff); and NUS pulses (chickpea, lentil, faba bean, cowpea, grass pea, pigeon pea, groundnut) and others (sesame, cactus pear, date palm). Major dryland food crops (barley, lentil, faba bean, grass pea, wheat, chickpea) are featured throughout.

2.2 Integrated data sets/modules

Five linked data sets/modules were assembled. Module 1: FAOSTAT Food Balance Sheets (2010–2023) at country-level dietary energy supply (DES), protein supply, food-group contributions, and cereal import dependence (FAO Food Balance Sheet, 2025). Module 2: FAO AQUASTAT (2026) for water withdrawal stress (SDG 6.4.2) and agricultural withdrawal shares. Module 3: International Energy Agency (IEA)/World Bank Tracking SDG7 (World Bank Group, 2021) for rural electricity access and irrigation energy use intensity; Chiarelli et al. (2026) and Zhang et al. (2026) for crop-specific irrigation energy use by fuel type. Module 4: USDA Food Data Central (USDA FDC, 2026) and FAO/INFOODS WAFCT (2019) for standardized nutrient profiles. Module 5: FAOSTAT Crops and Livestock Products (2024) for harvested area, yield, and water productivity inputs (FAOSTAT, 2025).

2.3 Analytical computation

Three integrated computations were applied.

1. Nutritional Water Productivity (NWP, kcal m^{-3} or g m^{-3}) was computed as $\text{NWP} = \text{WP} \times \text{NC}$, where WP (kg m^{-3}) is the water productivity derived from FAO-56 reference evapotranspiration (Allen et al., 1998) and NC is nutrient content per kg yield (USDA FDC, 2026).

$$\text{NWP} (\text{kcal m}^{-3} \text{ or } \text{g protein m}^{-3}) = \text{WP} (\text{kg m}^{-3}) \times \text{NC} (\text{kcal kg}^{-1} \text{ or } \text{g protein kg}^{-1}) \dots \dots \dots (1)$$

where: WP = crop water productivity (kg m^{-3}) from FAO-56 ET, NC = nutrient content per kg of harvested crop yield.

2. Technical Energy Use Intensity (TEI, kWh per 1,000 kcal) aggregates published energy coefficients across five value-chain stages: irrigation/pumping, processing/milling, drying/storage, transport, and cooking (Chiarelli et al., 2026; FAO, 2011; Mushtaq et al., 2009).

$$\text{TEI} (\text{kWh per 1,000 kcal}) = \sum e_i \text{ (i = irrigation/pumping, processing/milling, drying/storage, transport, cooking) } \dots \dots \dots (2)$$

where: e_i = stage-specific energy coefficient (kWh per 1,000 kcal delivered) from published values (Chiarelli et al., 2026; Mushtaq et al., 2009; FAO, 2011).

3. The WEFN Nutrition Resilience Index (WEFN-NRI) is an equal-weighted composite of normalized (0–1) scores for diet diversity, water security, energy access, and import security across 36 countries.

Scenario modelling projected BAU, Water-Productivity Optimized (WPO), and Diversified and Renewable Energy (DRE) outcomes from 2020 to 2030.

$$\text{WEFN-NRI} = \frac{1}{4} (D + W + E + I) \dots \dots \dots (3)$$

where: D = diet diversity score (0–1); W = water security score (0–1); E = energy access score (0–1); I = import security score (0–1); all components normalised to a 0–1 scale across 36 countries. BAU = Business-as-Usual; WPO = Water-Productivity Optimised; DRE = Diversified + Renewable Energy. Agronomic, seed system, and science impact scores (0–5 scale) were derived from structured expert synthesis and published literature (Devkota et al., 2025; Hobbs et al., 2008; Thierfelder et al., 2017).

3. RESULTS AND DISCUSSION

3.1 The water element of nexus: Stress, withdrawal, and irrigation productivity

Table 1 presents WEFN Nexus pressure indicators by region. Northern Africa records critical water stress at 121% of renewable resources and Western Asia at 65.1%, against a global average of 18% (AQUASTAT, 2026). Iran (92.95%), Egypt (77.50%), and Iraq (42.42%) operate at or beyond sustainable withdrawal limits, while 12 of 18 MENA countries face critical or high stress. SSA averages only 4.3% water stress, masking occasional seasonal deficits in the Sahel. Renewable freshwater per capita averages just 304 m³/year in MENA versus 1,072 m³/year in SSA. Agricultural water withdrawal constitutes 85.2% of total freshwater use in MENA and 73.8% in SSA drylands, making crop portfolio decisions to be the primary lever for water savings. Irrigation water productivity averages 12.8 USD/m³ in MENA and 8.4 USD/m³ in SSA, both far below the global mean of 21.5 USD/m³ (FAOSTAT, 2025).

Table 1. WEFN nexus pressure indicators by dimension and region (2022–2023)

Dimension	Indicator	MENA	SSA Drylands
WATER			
	Water stress (% renewable resources)	69.3 (N. Africa: 121%)	4.3
	Agricultural water withdrawal (% total)	85.2	73.8
	Renewable freshwater per capita (m ³ /yr)	304	1,072
	Countries with critical/high water stress	12 of 18	1 of 18
	Irrigation water productivity (USD/m ³)	12.8	8.4
ENERGY			
	Rural electricity access (%)	95.1	33.2
	Irrigation energy use intensity (GJ/ha)	8.4	2.6
	Diesel-powered irrigation (%)	26.4	67.4
	Renewable irrigation energy share (%)	18	12
FOOD / NUTRITION			
	Dietary energy supply (kcal/capita/day)	3,124	2,361
	Undernourishment prevalence (%)	10.9	22.8
	Cereal share of dietary energy (%)	43.8	57.4
	Cereal import dependence (%)	59.4	26.1
	Pulse protein share of total protein (%)	13.1	20.9

Sources: FAO AQUASTAT (2026); World Bank WDI (2026); FAOSTAT (2025); IEA Tracking SDG7 (2021).

3.2 The energy element of nexus: Access, irrigation energy, and value-chain

Two distinct energy constraint profiles emerged (Table 1). In MENA, rural electricity access averages 95.1% and the primary challenge is deep groundwater pumping: the region records the highest irrigation energy globally at 8.4 GJ/ha (Chiarelli et al., 2026), driven by fossil aquifer extraction, pressurized irrigation, and coastal desalination. In SSA, only 33.2% of rural households have electricity, Chad (4.8%), Niger (8.4%), Burkina Faso (9.8%), and 565 million people lack access entirely, directly constraining irrigation, processing, cold storage, and food preparation (World Bank Group, 2021).

Technical energy analysis (Table 2) reveals that irrigated rice carries the highest energy burden at 0.65 kWh/1,000 kcal, dominated by pumping (0.25 kWh/1,000 kcal) and cooking (0.15 kWh/1,000 kcal). Irrigated lentil and cowpea (0.38 kWh/1,000 kcal) are 42% lower than rice; chickpea (0.30 kWh/1,000 kcal) achieves 54% lower energy use intensity. A critical cross-dimensional insight is the water–energy co-efficiency (Pearson $r = 0.88$ ($n = 11$ representative crops)): crops requiring less irrigation water also require proportionally less pumping energy, so dietary diversification toward pulses and dryland cereals simultaneously reduces both water stress and energy consumption, a compounded Nexus co-benefit. Solar irrigation costs declined 89% between 2010 and 2023 and breakeven versus diesel has been achieved in more than 80% of SSA locations (Xie et al., 2021), with solar–NUS combinations offering the strongest compound co-benefit.

Table 2. Technical energy use intensity by value chain. Values expressed in kWh per 1,000 kcal delivered.

Stage	Rice (irrigated)	Wheat (irrigated)	Wheat (rainfed)	Sorghum (rainfed)	Lentil (irrigated)	Cowpea (rainfed)
Irrigation/pumping	0.25	0.18	0.00	0.02	0.09	0.08
Processing/milling	0.12	0.08	0.08	0.10	0.07	0.06
Drying/storage	0.08	0.05	0.05	0.05	0.06	0.07
Transport	0.05	0.04	0.04	0.03	0.04	0.03
Cooking	0.15	0.06	0.06	0.13	0.12	0.14
TOTAL	0.65	0.41	0.23	0.33	0.38	0.38
Saving vs. rice	—	−37%	−65%	−49%	−42%	−42%

Sources: Chiarelli et al., (2026); FAO (FAO, 2011); Mushtaq et al., (2009)

3.3 The food and nutrition element of nexus: Dietary energy supply and nutritional water productivity

MENA's DES rose from 2,950 to 3,124 kcal/capita/day (2010–2023), exceeding the 2,500 kcal adequacy threshold, but is concentrated in cereals (43.8%) imported to 59.4%, nearly three-fifths of cereal consumption. SSA's DES rose from 2,248 to 2,361 kcal/capita/day, remaining below adequacy, with 57.4% from cereals and undernourishment at 22.8%. Africa's average DES of 2,556 kcal/capita/day (FAOSTAT, 2025) remained 460 kcal below the global average of 3,016 kcal/capita/day.

Nutritional water productivity (NWP) analysis (Table 3) reveals decisive cross-crop differences. Grass pea delivers 5,550 kcal m^{−3} and 472 g protein m^{−3} under dryland conditions, followed by cowpea (4,800 kcal; 336 g m^{−3}) and lentil (4,413 kcal; 323 g m^{−3}). Across all pulses, average protein water productivity (WP) (324 g m^{−3}) exceeds dryland-adapted cereals (177 g m^{−3}) by 1.8 times and strategic staples (86 g m^{−3}) by 3.8 times. Pearl millet achieves the highest caloric WP (7,560 kcal m^{−3}) more than 5 times that of rice (1,440 kcal m^{−3}) and 2.8 times that of irrigated wheat (2,725 kcal m^{−3}), combined with the highest iron density of any staple food (8.0 mg/100 g). Iron WP for cowpea (119 mg m^{−3}) is 4.1 times that of wheat (29.2 mg m^{−3}). Dryland-adapted cereals average 5,633 kcal m^{−3} caloric WP, nearly 4 times that of rice (3.9) and 2.1 times that of irrigated wheat.

3.4 Integrated WEFN nexus analysis: Accounting matrix and vulnerability cluster

The WEFN Accounting Matrix integrates all three elements of water, energy and food-nutrition simultaneously. Three distinct vulnerability clusters emerged.

- Cluster 1 (Water-Import Exposed MENA): Egypt, Iran, Jordan, Saudi Arabia, UAE, and Qatar face critical water stress combined with near-total cereal import dependence, generating extreme supply disruption risk (Table 3a).
- Cluster 2 (Hunger-Energy Deficient SSA): Chad, Niger, Burkina Faso, and Somalia exhibit undernourishment exceeding 35% alongside rural electricity below 25%, creating severe combined food-energy deprivation (Table 3b).
- Cluster 3 (Multi-Dimensionally Stressed): Sudan, Yemen, and Syria face simultaneous water stress, hunger, and energy insecurity compounded by conflicts. These profiles confirm that the current policies are ineffective. The water–energy co-efficiency of dietary diversification, replacing 20% of imported rice area in MENA region with domestic pulses and dryland cereals would reduce water withdrawals by 8–14 km³/year and irrigation energy use intensity by 12–18%, provides the integrating logic connecting both Clusters 1 and 2 simultaneously.

Table 3a. Nutritional water productivity (NWP) by crop group and selected crops – MENA region (primarily irrigated systems)

Crop Group / Crop	Water req. (m ³ kg ⁻¹)	Caloric WP (kcal m ⁻³)	Protein WP (g m ⁻³)	Iron WP (mg m ⁻³)	TEI (kWh/1,000 kcal)
Strategic Staples					
Wheat (irrigated)	1.20	2,725	114	29.2	0.41
Rice (irrigated)	2.50	1,440	26	3.2	0.65
Maize (irrigated)	0.85	4,282	110	31.6	0.46
Average	1.52	2,816	83	21.3	0.51
MENA Dryland Cereal					
Barley (irrigated/rainfed)	1.10	3,227	110	35.5	0.38
NUS Pulses					
Lentil (irrigated)	0.80	4,413	323	81.3	0.38
Chickpea (irrigated)	0.90	4,200	228	54.4	0.30
Faba bean (irrigated)	1.00	3,410	261	67.0	0.38
Grass pea (rainfed)	0.60	5,550	472	95.0	0.31
Average NUS Pulses	0.83	4,393	321	74.4	0.34
Ratio: NUS Pulses / Staples	0.55	1.56	3.87	3.49	0.67

Table 3b. Nutritional water productivity (NWP) by crop group and selected crops – SSA drylands (primarily rainfed systems)

Crop Group / Crop	Water req. (m ³ kg ⁻¹)	Caloric WP (kcal m ⁻³)	Protein WP (g m ⁻³)	Iron WP (mg m ⁻³)	TEI (kWh/1,000 kcal)
Strategic Staple					
Maize (rainfed)	0.80	4,563	118	33.8	0.45
SSA Dryland-Adapted Cereals					
Sorghum (rainfed)	0.60	5,483	188	56.7	0.33
Pearl millet (rainfed)	0.50	7,560	220	160.0	0.37
Teff (rainfed)	0.60	6,117	222	127.0	0.38
Average Cereals	0.57	6,387	210	114.6	0.36
NUS Pulses					
Cowpea (rainfed)	0.70	4,800	336	119.0	0.38
Grass pea (rainfed)	0.60	5,550	472	95.0	0.31
Pigeon pea (rainfed)	0.75	4,533	286	68.0	0.36
Faba bean (rainfed)	1.00	3,410	261	67.0	0.38
Average NUS Pulses	0.76	4,573	339	87.3	0.36
Ratio: NUS Pulses / Maize	0.95	1.00	2.87	2.58	0.80

NWP = WP × NC (Renault & Wallender, 2000); WP from FAO-56 ETc (Allen et al., 1998); NC from USDA FDC (USDA FDC, 2026) and FAO/INFOODS WAFCT(2019).

3.5 Agronomic, seed system and technological pathways WEFN-NEXUS gain

NUS crop scaling in the WEFN Nexus is not primarily a single-sector challenge but a multi-dimensional science and technology integration problem (Table 4). Expert-assessed impact scoring across twelve intervention categories and eight NUS crops (chickpea, grass pea, sorghum, pearl millet, faba bean, lentil, cowpea, teff) reveals that four domains hold the highest potential: soil and conservation management, water management, seed systems and agronomic packages use, and digital and frontier crop science application.

Conservation agriculture, soil health, and biological nitrogen fixation. NUS crop compatibility with conservation agriculture (CA: no-till, mulching, diversified rotations) scores 3.6–4.5/5 versus the conventional staple crop baseline (3.0/5; Table 4). Rhizobium/mycorrhizal inoculants achieve soil health scores of 4.2–4.8/5 for grass pea and cowpea, delivering +24% yield gains and +12% water productivity increase while eliminating synthetic N fertilizer application. Integrated soil fertility management (ISFM) combined with conservation agriculture (CA) and biochar achieves carbon sequestration of 0.4–1.4 t C ha⁻¹ yr⁻¹ (Devkota et al., 2022). Supplemental irrigation (60–100 mm/season) delivers the highest WP gain (+45%). Solar micro-drip irrigation delivers the largest absolute WP improvement (+54%), but its adoption remains low (2.0/5) relative to its potential impact (2.8–4.2/5). This adoption–impact gap makes solar micro-drip irrigation the highest-priority capital investment for NUS intensification under energy-transition pathways.

Seed systems, good agronomic practices, and other NUS recommendations. Improved seed access and availability through improved seed systems and integrated agronomic packages are foundational to NUS scaling but remain critically underdeveloped for most NUS crops. The 27 recommendations from the ICARDA organized international expert conference on NUS crops for MENA and SSA drylands (Devkota et al., 2025; [chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://icarda.org/sites/default/files/2024-02/nus-recommendations.pdf](https://icarda.org/sites/default/files/2024-02/nus-recommendations.pdf)) addressed four co-equal priority

domains: (i) formal breeding programs for dryland-adapted NUS varieties targeting heat tolerance, drought resistance, and improved nutritional profiles; (ii) formal (certified) and informal (farmer-to-farmer exchange) seed systems to ensure farmers timely access to quality certified seed; (iii) integrated agronomic management packages encompassing optimal sowing dates, plant densities, fertilization, water management schedules, and crop rotations tailored to local agro-ecologies; and (iv) postharvest processing, value-chain infrastructure, and market linkage development as investment priorities equal in importance to agronomic solutions. ICARDA field experiments in Morocco demonstrated that NUS-based intercropping systems (lentil-quinoa) delivered significantly higher gross margins and nutritional yields per unit of water used than wheat monocultures (Devkota et al., 2025), directly supporting the WEFN Nexus triple-win hypothesis.

Digital advisory and frontier science. Remote sensing and AI-based advisory platforms show strong impact potential for NUS crops (3.2–4.0/5), but current adoption remains low, particularly for remote sensing (1.8/5). This indicates a clear need to prioritize adoption, capacity building, and deployment pathways. Speed breeding and genomic selection, already proven in chickpea and lentil with a threefold increase in genetic gain (increased productivity from gene selection), should be extended to NUS crops such as cowpea, pearl millet, teff, and grass pea. Meanwhile, readiness for CRISPR (gene-editing technology that allows scientists to precisely alter, delete, or replace specific DNA sequences within a living organism) and high-throughput phenotyping (HTP; automated, rapid screening of large numbers of plant traits using advanced imaging and technology) averages only 2.2/5 across NUS crops, compared with more than 4.0/5 for major conventional staples. This represents one of the largest frontier-science investment gaps for scaling NUS crops.

Table 4. Agronomic practice, seed system, and science-technology priorities for WEFN-NEXUS gain

Domain	Key Practice	Impact (0–5)	Adoption (0–5)	Primary WEFN Nexus Benefit	Region
Soil health	Conservation Agriculture (no-till + mulching + rotation) what rotation	4.2–4.5	2.2	WP +22–28%; soil C 0.4–0.8 t/ha/yr; NUS CA compact. 3.6–4.5/5 vs 3.0/5 conventional	Both
Crop establishment	Raised-bed / Furrow Planting	3.4–4.0	3.0	WP +22–28%; improved drainage and root-zone health	Both
Soil biology	Rhizobium / Mycorrhizal Inoculants	4.2–4.8	2.0	+24% yield; biological nitrogen fixation (BNF) eliminates synthetic N; soil health 4.6–4.8/5	Both
Soil health	ISFM + Organic Input / Biochar	4.0–4.8	2.8	Soil C 0.8–1.4 t/ha/yr; health score 4.6–4.8/5; C sequestration	SSA
Water	Supplemental Irrigation (60–100 mm/season)	3.8–4.4	3.8	WP +45%; highest single-practice gain; enables NUS intensification	SSA rainfed
Water	Deficit Irrigation (40–60% ETC)	3.4–4.2	2.8	WP +32%; water saving 20–35%; critical for MENA water scarcity cluster	MENA
Water	In-situ Water Harvesting (tied ridges, micro-basins)	3.6–4.8	2.8	WP +38%; key for SSA Cluster 2 countries with no irrigation access	SSA
Water+Energy	Solar Drip Micro-Irrigation	2.8–4.2	2.0	WP +54%; 40–60% energy cost reduction; solar–NUS co-benefit; top investment priority	SSA
Agronomy & seed	Good Agronomic Practices & Seed Systems (NUS)	4.0–4.6	2.4	27 recommendations (Devkota et al., 2025): formal variety improvement, seed access, optimal agronomic packages, market linkage	Both

Domain	Key Practice	Impact (0–5)	Adoption (0–5)	Primary WEFN Nexus Benefit	Region
Digital	Remote Sensing + artificial intelligence (AI) Crop Advisory	3.2–4.0	1.8	Precision water/nutrient management; high impact, low adoption = priority scale-up	Both
Frontier	Speed Breeding + Genomic Selection	2.8–4.4	1.6	+3× genetic gain rate (proven in chickpea/lentil); urgent extension to cowpea, pearl millet, teff, grasspea	Both
Frontier	CRISPR + High-Throughput Phenotyping	2.0–4.0	1.4	Readiness 2.2/5 vs >4.0/5 conventional; largest frontier R&D investment gap for NUS	Both

Impact and Adoption: expert-assessed 0–5 scale. WP = water productivity. Sources: Hobbs et al. (2008); Thierfelder et al. (2017); Devkota et al. (Devkota et al., 2025); Varshney et al. (Varshney et al., 2021); Rusinamhodzi et al. (2011).

3.6 Scenario modelling projection to 2030: WEFN triple-win pathways

Three scenarios quantify the multi-dimensional co-benefits of WEFN integration (Table 5). The business-as-usual (BAU) scenario projects water stress to increase by 28% in MENA, import dependence to rise by 12 %, with only 6% marginal diet diversity improvement, and WEFN-NRI falling 8% by 2030. The *water-productivity optimized* (WPO) scenario where, 20% of the rice area is substituted by pulses and dryland cereals, combined with deficit irrigation, achieved 40% water stress reduction, 30% renewable irrigation energy saving, 38% diet diversity improvement, 26 % less import, and improved 31% WEFN-NRI. The diversified + renewable energy (DRE) scenario combining NUS crops, solar drip irrigation, seed system investment, and digital precision advisory, achieved: 50% water stress reduction, 45% renewable irrigation energy saving, 67% diet diversity improvement, 45 % less import, reduction by 9.4 % of undernourishment, and 55% WEFN-NRI improvement against the 2023 baseline. These results confirm the WEFN Nexus hypothesis: dietary diversification toward NUS, associated with the agronomic, seed system, and science investments (Table 5), constitutes a genuine WEFN triple-win.

BAU = Business-as-Usual; WPO = Water-Productivity Optimized (20% rice area → pulses + deficit irrigation); DRE = Diversified + Renewable Energy (WPO + NUS + solar irrigation + seed systems + digital advisory). Baseline = 2023.

Table 5. Scenario analysis: WEFN nexus outcomes under three portfolio scenarios to 2030

Nexus Indicator	BAU 2030	WPO 2030	DRE 2030
WATER DIMENSION			
Agricultural water stress change (% vs 2020)	+28%	–40%	–50%
Caloric water productivity improvement (%)	0%	+28%	+42%
ENERGY DIMENSION			
Renewable irrigation energy share (%)	18%	30%	45%
Irrigation energy use intensity change (% vs 2020)	0%	–12%	–28%
FOOD / NUTRITION DIMENSION			
Diet diversity index improvement (% vs 2020)	+6%	+38%	+67%
Cereal import dependence change (%)	+12 %	–26 %	–45 %
Undernourishment reduction (%)	–1.2 %	–5.8 %	–9.4 %
WEFN Nutrition Resilience Index (WEFN-NRI) change (% vs 2023)	–8%	+31%	+55%

4. POLICY IMPLICATIONS

The WEFN Nexus evidence generated in this study has direct implications for the priorities of the ICID WEFN-Nexus Working Group. For **MENA water-scarce systems (Cluster 1)**, five policy priorities emerge: (i) water pricing to encourage substitution of high water-demanding staples, particularly rice, with pulses and dryland cereals; (ii) scaling deficit irrigation to reduce freshwater withdrawals by 20–35%; (iii) accelerating the transition to solar pumping to reduce dependence on fossil-fuel-based irrigation energy and exposure to fuel-price volatility; (iv) promote efficient irrigation technologies through incentivization; and (v) redirecting food subsidy policies toward domestically producible NUS crops that can improve nutrition while reducing water and import pressures.

For **SSA rainfed and drought-prone systems (Cluster 2)**, priority actions include: (i) expanding supplemental irrigation and in-situ water harvesting to support NUS intensification; (ii) promoting off-grid solar drip irrigation, particularly in areas where diesel currently supports 67% of irrigated land; (iii) strengthening informal seed systems and integrated agronomic management packages for cowpea, pearl millet, teff, and grass pea, thereby operationalizing the 27 NUS recommendations of Devkota et al. (Devkota et al., 2025); and (iv) investing in postharvest processing and value-chain infrastructure to improve nutritional water productivity from field to plate.

Across both clusters, Table 4 identifies three high-priority science and investment domains: (a) conservation agriculture, integrated soil fertility management, and Rhizobium inoculation packages, which show high impact potential (4.2–4.8/5) but low-to-moderate adoption (2.0–2.8/5); (b) solar drip micro-irrigation, with strong impact potential (2.8–4.2/5) but low adoption (2.0/5); and (c) speed breeding, CRISPR, and high-throughput phenotyping for NUS crops, where impact potential is high (2.8–4.4/5) but adoption remains very limited (1.4–1.6/5). These adoption–impact gaps indicate where targeted investment could produce the greatest WEFN Nexus gains.

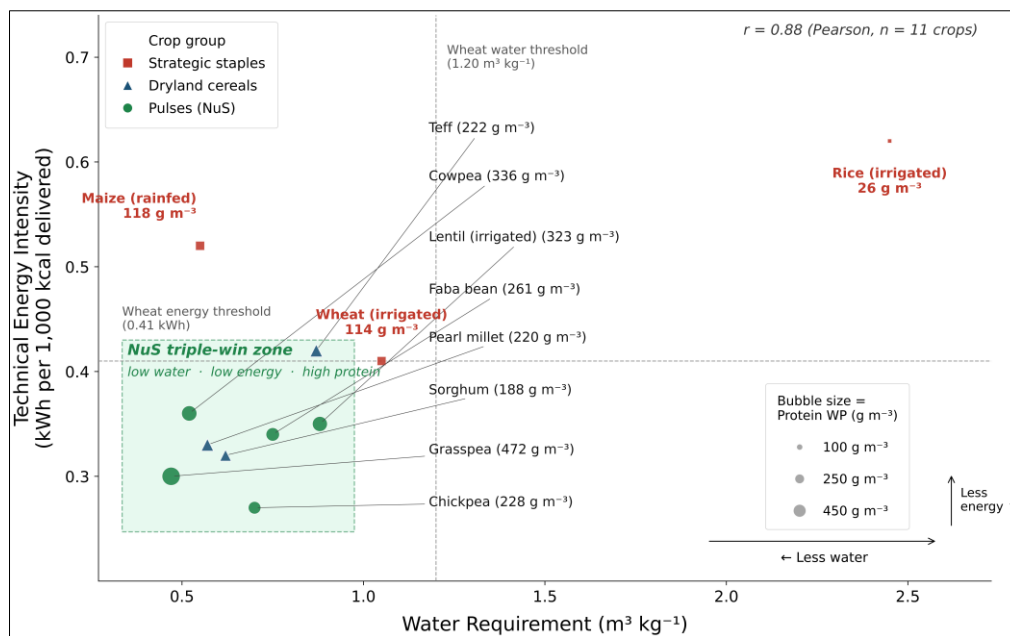


Figure 1. Water–Energy–Nutrition Co-efficiency for 11 Food Crops. Crops are plotted by water requirement (x-axis) and technical energy use intensity (y-axis; kWh per 1,000 kcal delivered). Bubble size is proportional to protein water productivity (g protein m⁻³). Pulses (NUS) and dryland-adapted cereals cluster in the lower-left 'triple-win zone' (green box), combining low water demand (0.50–1.00 m³ kg⁻¹), low energy intensity (0.30–0.38 kWh per 1,000 kcal), and high protein productivity per m³ (188–472 g m⁻³). Strategic staples (red) occupy the high-water, higher-energy upper-right region. Dashed lines show irrigated-wheat thresholds (x: 1.20 m³ kg⁻¹; y: 0.41 kWh). Water–energy Pearson $r = 0.88$ ($n = 11$ crops shown). All data from Tables 2–3; sources as cited earlier.

ICARDA's dryland mandate—covering climate-smart crop improvement, seed-system development, integrated agronomic packages, supplemental irrigation, conservation agriculture with raised-bed systems, and digital advisory platforms—aligns closely with the WEFN Nexus triple-win pathways quantified in Tables 1–5. The WEFN Accounting Matrix, WEFN-NRI vulnerability typology, and five quantitative tables provide ICID, ICARDA, and national policymakers with practical, data-integrated tools to guide investment and policy design in resource-constrained dryland regions. These tools directly support progress toward SDG 2 on Zero Hunger and SDG 7 on Affordable and Clean Energy, while also strengthening water and nutrition security across MENA and SSA.

5. CONCLUSIONS

This paper developed an operationalized WEFN Nexus Accounting Matrix with equal analytical weight across all four WEFN Nexus elements (Tables 1–5 and Figure 1). Five integrated conclusions can be summarized as:

(1) Water: Northern Africa records critical withdrawal stress at 121%; MENA withdraws 85.2% of freshwater for agriculture; renewable freshwater per capita averages 304 m³/year. Pulses and dryland cereals offer 40–60% lower water demand per kilogram grain than strategic staples.

(2) Energy: SSA accounts for 85% of the global electricity access deficit (565 million people); diesel irrigation dominates 67% of SSA irrigated area; MENA irrigation energy use intensity (8.4 GJ/ha) is the highest globally. Water–energy co-efficiency means dietary diversification simultaneously reduces both; solar transition achieves 40–60% cost reduction.

(3) Food/Nutrition: SSA's dietary energy supply averages 2,556 kcal capita⁻¹ day⁻¹), which is about 460 kcal below the global average, and more than 20% of the region's population faced hunger in 2024. Pulses provide a major nutrition-efficiency advantage, producing 3.8 times more protein per unit of water than strategic staples, 324 versus 86 g m⁻³, while requiring 42–54% less technical energy than irrigated rice.

(4) Agronomic, seed system, and science dimension: Conservation agriculture compatibility, rated at 3.6–4.5/5, together with biological nitrogen fixation, deficit irrigation, and Rhizobium inoculation, can generate combined soil, water, and nutrition co-benefits. The 27 NUS recommendations of Devkota et al. (2025) identify seed systems and integrated agronomic packages as investment priorities equal in importance to crop performance. Digital advisory systems and frontier genomic science remain among the most urgent investment gaps for scaling NUS crops.

(5) Scenario outcomes: Table 5 shows that the diversified + renewable energy (DRE) scenario could deliver substantial improvements by 2030 compared with the 2023 baseline: a 50% reduction in water stress, 67% improvement in dietary diversity, 45% reduction in import dependence, 45% renewable irrigation-energy savings, 9.4% reduction in undernourishment, and 55% improvement in the WEFN-NRI. These results indicate that integrated diversification, renewable energy, seed-system investment, and digital precision advisory can generate a strong multi-dimensional WEFN Nexus gain across water, energy, food, and nutrition security.

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A NEXUS-BASED OPTIMIZATION OF WATER SUPPLY, HYDROPOWER, AND AGRICULTURAL LAND-USE CONVERSION

Chia-Wen Wu¹ and Frederick N.-F. Chou²

ABSTRACT

This study investigates how system-level energy performance can be improved in a coupled water–energy–food (WEF) nexus while maintaining water-supply security and explicitly considering food-sector implications. The Dajia–Daan River system in central Taiwan is used as a practical case study because it physically links reservoir operation, hydropower generation, pumped-storage regulation, multi-source water supply, and agricultural irrigation. A simulation–optimization framework is developed in which water security is treated as a constraint, net energy performance is defined as the objective function, and agricultural land-use conversion is incorporated as a food-sector adaptation pathway.

The results reveal a critical trade-off: conservative reservoir operation can protect water supply in ordinary years, but it suppresses hydropower generation and increases reliance on energy-intensive water sources. Under the optimized agricultural-conversion scenario, public water-supply reliability is maintained at 78%, while annual net energy production increases by approximately 175×10^6 kWh compared with the baseline scenario with pumped-storage operation alone. The reduction in irrigation demand also improves operational flexibility in the coupled reservoir system.

From the food-sector perspective, agricultural transformation should not be interpreted simply as a sacrifice of food production. Conversion of rice paddies may support wheat production, which is relevant to Taiwan's import-dependent staple-food structure, or high-value flower cultivation, which is locally relevant in the Houli area. However, the WEF outcome depends strongly on crop choice and cultivation intensity. Low-energy or open-field flower cultivation can preserve most system-level energy gains, whereas electricity-intensive greenhouse cultivation may offset them.

Keywords: water allocation, hydropower and pumped-storage unit, agricultural land conversion, simulation, optimisation, Taiwan.

1. INTRODUCTION

The water–energy–food (WEF) nexus provides a useful framework for understanding interactions among water allocation, energy production, and agricultural systems. Practical implementation of the WEF nexus requires case studies in which sectoral interactions can be explicitly represented through real infrastructure, operating rules, and policy constraints (Bazilian et al., 2011; Hoff, 2011; Allouche et al., 2015; Endo et al., 2017; Simpson & Jewitt, 2019).

In reservoir-based river basins, water supply security, hydropower generation, pumped-storage regulation, and irrigation demand are often physically connected. In such systems, WEF analysis should not only describe sectoral interactions, but also evaluate how operational decisions and land-use adjustments affect water security, energy performance, and food-sector outcomes. This study argues that in basins where water resources are inherently limited, the allocation of energy and agricultural activities must ultimately be governed by water availability and operational constraints. Taiwan provides a relevant setting for a water-resources-oriented WEF case study. During 2015–2024, Taiwan's average

¹ Adjunct assistant professor, Department of Hydraulic and Ocean Engineering, National Cheng Kung University; E-mail: chiawenwu1977@gmail.com

² Adjunct professor, Department of Hydraulic and Ocean engineering, National Cheng Kung University; E-mail: chounf@gmail.com

annual precipitation was approximately 89.183 billion m³, while the available runoff after evaporation and infiltration losses was estimated at 66.268 billion m³. The main challenge is therefore not only total water availability, but also the seasonal concentration of rainfall and the spatial mismatch between water sources and major demands. The average annual water use was 16.017 billion m³, of which agricultural water use accounted for 11.229 billion m³ (70.11%), domestic and public water-supply use for 3.176 billion m³ (19.83%), and industrial water use for 1.612 billion m³ (10.06%). Agriculture therefore dominates total water use, but public water-supply systems also carry increasingly rigid domestic, commercial, and high-tech industrial demands.

The energy challenges in Taiwan further support the use of water resources as the entry point for WEF analysis. In 2024, Taiwan's total electricity generation was approximately 289.2 billion kWh, whereas conventional hydropower generation was only about 4.21 billion kWh. Hydropower therefore contributes a limited share of total electricity supply, but it provides important peak-period generation and system-regulation functions. As solar and wind power increase, hydropower and pumped-storage regulation become more important for absorbing variability and supporting grid flexibility. From the water-resources perspective, the practical contribution is not to solve the energy gap by hydropower alone, but to avoid energy-intensive water-supply strategies and to enhance hydropower and pumped-storage benefits within a water-security boundary.

Similarly, Taiwan's food-security problem is structural rather than a uniform shortage of all crops. In 2024, domestic rice production was 1.219 million tons, whereas net food supply of rice was 0.993 million tons, indicating a relatively sufficient domestic rice base. In contrast, wheat is almost entirely import-dependent: domestic wheat production was only 0.002 million tons, while net food supply reached 0.866 million tons. Because paddy rice requires substantial irrigation water, crop conversion from rice to wheat or other strategic crops can be interpreted not merely as a reduction of agricultural water use, but also as a food-sector adjustment strategy within the WEF nexus.

This study presents a practical WEF case study of the Dajia–Daan River system in central Taiwan. A reservoir–river simulation framework is used to evaluate water allocation, reservoir operation, hydropower generation, pumped-storage operation, and water-supply energy consumption under different strategies. Agricultural conversion is represented through an area-based approximation to estimate changes in irrigation demand, rice production, wheat production, and additional electricity demand associated with greenhouse flower cultivation. The objective is to demonstrate how reservoir operation and agricultural adjustment can jointly improve energy performance while maintaining water security and explicitly accounting for food-sector trade-offs. In the proposed framework, water security is treated as the protected boundary, energy performance as the operational objective, and agricultural conversion as the food-sector adaptation pathway. This setting reflects a scale-mismatch interpretation of the WEF nexus. Water security is regionally binding and quantifiable, whereas energy and food security are shaped by broader grid, market, and trade systems. Thus, the energy contribution of the regional system is pursued within the water-security boundary, while land-use conversion is evaluated as a food-sector adjustment conditional on the maintenance of basic food-security requirements.

2. METHODS

The methodology consists of four components corresponding to the water, energy, and food elements of the nexus. These components are integrated into a simulation–optimization framework to compare alternative WEF strategies under water-security constraints.

2.1 Water allocation and reservoir rule curve simulation

The water component is simulated using WRASIM (Chou and Wu, 2010, 2014), which represents a water resources system as a reservoir–river network. The model is used to simulate daily public water supply, irrigation demand, reservoir storage, hydropower releases, water treatment plant production, reclaimed water, and downstream surplus flow. Water allocation is controlled by operating rules and priority coefficients while satisfying mass balance and capacity constraints.

Reservoir rule curves are represented through storage zones and corresponding operational priorities. They define how the system shifts among storage protection, public supply, irrigation supply, hydropower generation, and alternative water-source use under different water-availability conditions. Hydropower releases are treated as non-consumptive use because generated water can continue downstream where conveyance conditions permit (Labadie et al., 1986). Therefore, reservoir rule curves function not only as water-supply rules, but also as decision variables affecting hydropower generation, spill reduction, water-supply energy consumption, and drought robustness.

2.2 *Hydropower and pumped-storage operation*

The energy component includes both conventional hydropower generation and pumped-storage regulation. Conventional hydropower is affected by reservoir releases, hydraulic head, turbine capacity, and the duration of peak generation. Pumped-storage operation is represented because the Dajia River system is expected to support intraday renewable-energy regulation, particularly by using surplus daytime electricity to pump water to an upstream reservoir and generating electricity during peak-demand periods.

To represent this intraday operation within a daily water-allocation model, each day is divided into two sub-periods: an 8-hour pumping period and a 16-hour generation period. During the pumping period, water can be transferred from the downstream reservoir to the upstream reservoir when storage capacity and pumping capacity are available. During the generation period, water can be released for hydropower generation subject to reservoir storage, hydraulic head, turbine or release capacity, and specified peak-generation hours.

The maximum pumping or generation volume in each sub-period is constrained by the design capacity of the pumping or generation facilities, the effective hydraulic head, and the duration of operation. The daily energy generation is calculated from the simulated reservoir release volume, the average hydraulic head, and the overall efficiency of the generating units. Pumped-storage generation is interpreted primarily as an energy-regulation function rather than as an independent renewable-energy source, because pumping requires electricity input, which is assumed in this study to be sufficiently supplied by surplus renewable energy. This assumption reflects the role of pumped storage in absorbing surplus daytime solar power and supporting evening peak demand.

Energy consumption associated with public water supply is also included. Different water sources have different unit energy consumption values. Conventional reservoir-based or gravity-fed water treatment generally requires less energy, whereas river abstraction with high lifting head, reclaimed water, and desalination require progressively higher energy input. The annual energy consumption of water supply is calculated by multiplying the simulated water production from each source by its corresponding unit energy consumption. This links reservoir operation and water-source selection directly to system-wide energy performance.

2.3 *Agricultural land-use conversion and food-sector estimation*

Taiwan has implemented agricultural adjustment policies, including the Green Environmental Payment Program and the Big Granary Project, to reduce structural dependence on continuous paddy cultivation, encourage import-substitute crops, and improve domestic grain self-sufficiency. Under this policy context, agricultural conversion is treated not as an artificial reduction in irrigation demand, but as a stylized representation of an existing food-sector adjustment pathway.

The food component is represented through agricultural land-use conversion in the Houli irrigation district. This district is selected because reducing its irrigation demand allows more water to be diverted upstream and stored in Liyutan Reservoir for public water supply. Wheat and flower cultivation are examined as two representative conversion pathways. Wheat represents a food-security-oriented option, whereas flowers represent a locally relevant high-value crop already developed in the Houli area. The conversion effect is estimated using an area-based linear approximation. The converted area is used to estimate reductions in irrigation demand and rice production, potential wheat production, and

additional electricity demand from flower cultivation. For flowers, water demand is estimated using a planning-level irrigation requirement, while electricity demand is evaluated under two assumptions: a low-energy pathway derived from local agricultural production cost statistics and a high-electricity greenhouse benchmark. This two-level treatment examines whether agricultural conversion preserves or offsets the energy gains from water-system operation.

2.4 Optimization formulation and scenario design

The water, energy, and food components are integrated into a simulation–optimization framework. The main objective is to improve annual net energy performance while maintaining water security. Net energy performance is defined as hydropower generation minus energy consumption for water supply. The optimization problem can be expressed conceptually as:

$$\text{Maximize } EG-EC \quad (1)$$

Where EG is annual hydropower generation, EC is annual energy consumption for water supply, both of which can be determined by the simulation of water allocation and reservoir operations. The optimization is subject to water-security constraints. Public water supply must satisfy reliability and robustness requirements (Wu et al., 2026). Reliability is used to ensure that unacceptable public water shortages do not occur too frequently over the long-term simulation period. Robustness is used to ensure that the deficit in the most severe drought year does not exceed an acceptable threshold or baseline condition. These constraints reflect the principle that energy efficiency can be improved only within a non-negotiable water-security boundary.

This formulation reflects a scale-aware interpretation of the WEF nexus. Water security can be quantified at the regional supply-system scale, whereas energy and food security are generally governed at broader grid, market, import, and policy scales. Therefore, water security is imposed as the binding regional constraint, energy performance is used as the optimization objective, and agricultural conversion is evaluated through scenario-based food-sector implications rather than as a separate regional food-security constraint.

The main decision variables in the optimization include reservoir rule curves and hydropower operating hours. Agricultural conversion is introduced as a scenario-based structural adjustment. Rule curves determine when the system shifts between efficiency-oriented and security-oriented operation. Hydropower operating hours determine the extent to which water can be used for peak generation. Agricultural conversion determines the reduction in irrigation demand and the corresponding food-sector and energy implications.

3 CASE STUDY AND SCENARIO DESIGN

3.1 Dajia–Daan River system and WEF components

The Dajia–Daan River system in central Taiwan is selected as the case study because it physically connects public water supply, hydropower and pumped-storage operation, and agricultural irrigation. The Dajia River basin contains Deji Reservoir and a cascade of hydropower plants, including Qingshan, Guguan, and Tianlun. It is therefore the energy-oriented part of the system. The planned Guangming pumped-storage project uses Deji Reservoir as the upstream reservoir and Guguan Reservoir as the downstream reservoir, with a design discharge of 155 m³/s and an intended 4-hour peak-generation function.

The Daan River basin supports public water supply through Shilin Weir and Liyutan Reservoir. Water diverted at Shilin Weir can be conveyed to Liyutan Reservoir, which functions primarily as a public water-supply reservoir. The system supplies Taichung City through both Shigang Dam on the Dajia River and Liyutan Reservoir on the Daan River. By 2041, the projected public water demand, including neighbouring supply areas, is about 1.719 million m³/day.

The food component is represented by agricultural irrigation and land-use conversion. Irrigation districts in the Daan and Dajia basins are located mainly downstream of Shilin Weir and Shigang Dam. The Houli irrigation district, located downstream of Shilin Weir, is particularly important because reducing irrigation demand there allows more water to be diverted and stored in Liyutan Reservoir. This creates a direct linkage between agricultural adjustment, public water security, and hydropower flexibility.

In this case study, water security is represented by public water-supply reliability and drought robustness. Energy performance is represented by hydropower generation, pumped-storage regulation, and electricity consumed by water supply. Food-sector outcomes are represented by irrigation water demand, rice production, alternative crop production, and additional electricity demand from greenhouse cultivation.

Figure 1 summarizes the spatial and functional structure of the Dajia–Daan River water resources system used in this study. It shows how the energy-oriented Dajia River basin and the water-supply-oriented Daan River basin are connected through reservoir operation, diversion facilities, water treatment plants, irrigation districts, and downstream flow paths. The figure also identifies the Houli irrigation district as the key agricultural-conversion area, because reduced irrigation demand there can increase the water available for diversion and storage in Liyutan Reservoir. Thus, Figure 1 provides the physical basis for linking water allocation, hydropower and pumped-storage operation, and agricultural land-use conversion within the proposed WEF nexus framework.

3.2 Simulation scenarios

Four scenarios are designed to evaluate how operational and agricultural strategies affect the WEF system. Scenario A represents the conservative high-storage baseline. Deji Reservoir is operated at a high storage level, and reclaimed water is assumed to operate at a fixed capacity. This scenario prioritizes water supply security but provides limited flexibility for hydropower generation.

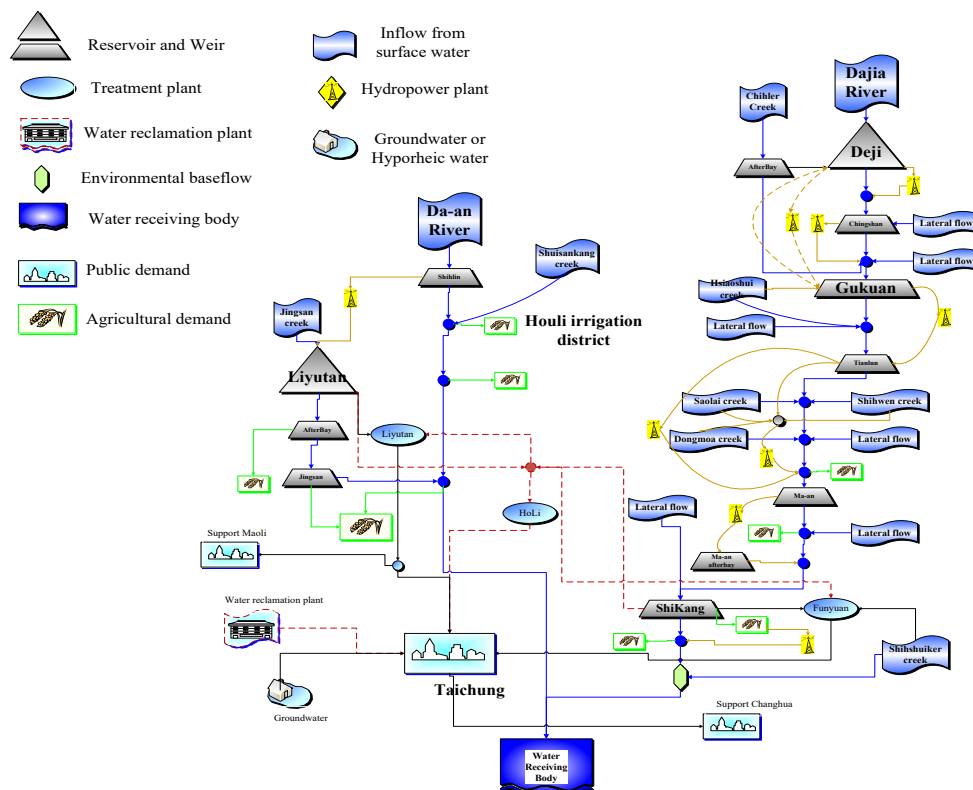


Figure 1. Network of the Daan and Dajia River water resources system

Scenario B adds the Guangming pumped-storage project to Scenario A. This scenario evaluates whether pumped storage can provide energy-regulation benefits when the underlying reservoir operation remains conservative.

Scenario C optimizes reservoir rule curves and hydropower operating hours under water-security constraints. In this scenario, the system is allowed to shift between efficiency-oriented and security-oriented operation according to reservoir storage conditions. Reclaimed water output and water treatment plant source selection are linked to the storage state of Liyutan Reservoir.

Scenario D introduces agricultural land-use conversion in the Houli irrigation district and re-optimizes reservoir operation. The reduction in irrigation demand allows more water to be diverted and stored in Liyutan Reservoir. This scenario evaluates whether food-sector adjustment can improve public water security and unlock hydropower and pumped-storage flexibility.

3.3 Agricultural conversion assumptions

For Scenario D, the Houli irrigation district is used as the agricultural conversion case. The district covers approximately 3,177 ha, of which about 2,890 ha are rice paddies. Annual rice production is approximately 0.02 million tons, accounting for about 1.6% of Taiwan's total rice production. The projected annual irrigation demand is approximately 173 million m³, while the average actual supply is about 145 million m³. This scenario is used to represent the upper bound of irrigation water saving.

Two conversion pathways are considered. Flower cultivation represents a locally relevant high-value crop pathway. If the converted area is allocated to flowers, annual irrigation demand is estimated at approximately 29 million m³. Electricity demand is evaluated using two assumptions: a low-energy local pathway of approximately 17.9 million kWh/year and a high-electricity greenhouse benchmark of approximately 404.6 million kWh/year. Wheat cultivation represents a food-security-oriented pathway. If the dry-season cropping period is allocated to wheat, annual irrigation demand is estimated at approximately 84 million m³, and potential wheat production is approximately 0.017 million tons/year. Wheat conversion is therefore used as a food-sector indicator rather than as a separate optimized cropping scenario.

4 RESULTS AND DISCUSSION

Table 1 summarizes the main performance indicators under the four scenarios. The results show how reservoir operation, pumped-storage regulation, and agricultural conversion jointly affect water security, energy performance, and food-sector outcomes in the system.

4.1 Water security effects

The results indicate that the conservative high-storage strategy does not necessarily provide the best overall WEF performance. Under Scenario A, public water-supply reliability reaches 76%, but the severe-drought deficit remains 57.0%, indicating that conservative storage alone cannot fully ensure drought robustness.

After pumped-storage operation is introduced in Scenario B, reliability increases to 80%, and the severe-drought deficit decreases to 48.5%. Scenario C, which optimizes reservoir rule curves and hydropower operating hours, maintains reliability at 76% and reduces the severe-drought deficit to 49.3%, showing that energy performance can be improved without substantially worsening water security. Scenario D further includes agricultural conversion in the Houli irrigation district. It maintains reliability at 78% and reduces the severe-drought deficit to 48.3%, indicating that reduced irrigation pressure can help preserve water-security performance while allowing more flexible reservoir operation.

Figure 2 shows the optimized reservoir rule curves for Scenario D, in which the horizontal axis is expressed as 36 ten-day periods in a year (three periods per month: days 1–10, 11–20, and the

remaining days of each month). For Deji Reservoir, the optimized rule curve remains at a relatively low storage level, around EL. 1370 m, during periods 18–21. This indicates that reservoir storage is intentionally drawn down and maintained at a low level during the wet season, thereby allowing greater operational flexibility for hydropower generation and pumped-storage operation. In contrast, the optimized rule curves for Liyutan Reservoir rise progressively from the beginning of the wet season, reflecting its role as the main public water-supply buffer in the coupled system. In Scenario D, the reduction in irrigation demand in the Houli district allows more water to be diverted and stored in Liyutan Reservoir, thereby supporting public water-supply reliability and drought robustness. Together, these optimized rule curves explain why Scenario D can increase net energy production while maintaining water-security performance.

Table 1. Simulation results for each scenario

Scenario	Water reliability (%)	Severe drought deficit (%)	Total hydropower (10^8 kWh/yr)	Public water-supply energy consumption (10^8 kWh/yr)	Food implication
A	76	57.0	21.9	1.2	No conversion
B	80	48.5	38.1	1.2	No conversion
C	76	49.3	38.5	1.1	No conversion
D	78	48.3	39.4	0.7	Rice -0.02 Mt/yr; Wheat $+0.017$ Mt/yr; Flower electricity: $+0.18 \times 10^8$ kWh/yr for low-energy pathway or $+4.05 \times 10^8$ kWh/yr for high-electricity greenhouse benchmark

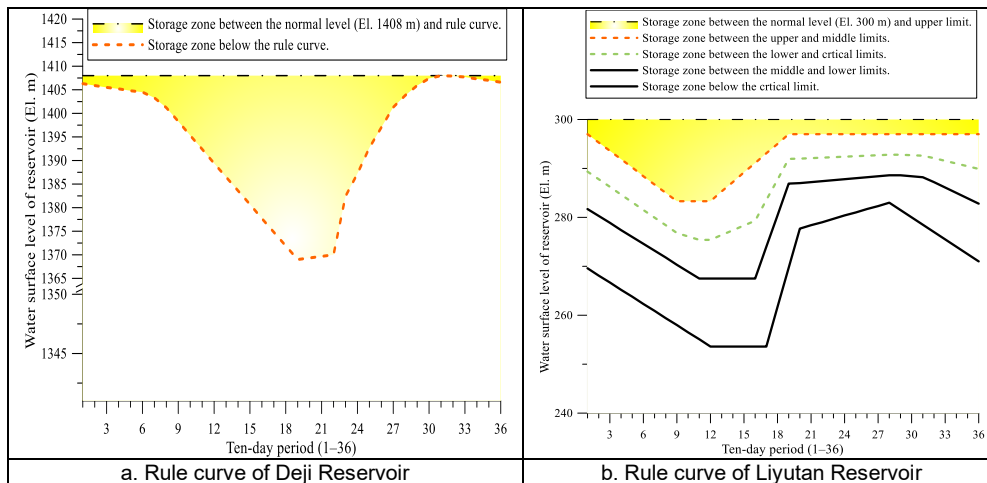


Figure 2. Optimized reservoir rule curves for Scenario D (dashed lines indicate optimized curves)

4.2 Energy performance effects

Energy performance differs substantially across the scenarios. Under Scenario A, total annual hydropower generation is 21.9×10^8 kWh/year, and net energy production is 20.7×10^8 kWh/year. Because Deji Reservoir is operated at a high storage level, additional hydropower releases are limited, and the daily peak generation duration at 80% exceedance probability is only 1.2 hours, which is insufficient to provide meaningful evening peak support after solar power output declines.

Scenario B introduces pumped-storage operation. Total hydropower generation increases to 38.1×10^8 kWh/year, net energy production increases to 36.9×10^8 kWh/year, and the daily peak generation duration at 80% exceedance probability increases to 4.4 hours, satisfying the intended regulation function. Scenario C further improves performance through rule-curve optimization. Compared with

Scenario B, hydropower generation increases from 38.1 to 38.5×10^8 kWh/year, while water-supply energy consumption decreases from 1.2 to 1.1×10^8 kWh/year.

Scenario D produces the highest net energy performance: hydropower generation increases to 39.4×10^8 kWh/year, water-supply energy consumption decreases to 0.7×10^8 kWh/year, and net energy production reaches 38.7×10^8 kWh/year. Compared with Scenario B, the net energy gain is approximately 1.75×10^8 kWh/year, mainly because agricultural conversion reduces irrigation demand and increases flexibility in the coupled Dajia–Daan system.

4.3 Food-sector implications

The food-sector results show that agricultural conversion should not be interpreted simply as sacrificing food production. In Scenario D, conversion in the Houli irrigation district is used to explore the upper bound of irrigation water saving. The district covers approximately 3,177 ha, of which about 2,890 ha are rice paddies. Annual rice production in the district is about 0.02 million tons, accounting for about 1.6% of Taiwan's total rice production of 1.2 million tons. The conversion therefore has a relatively limited effect on national rice production, but it has a large effect on local irrigation demand.

The irrigation demand of the Houli district is approximately 173 million m³/year, with an average actual supply of about 145 million m³/year. After conversion to flower cultivation, annual irrigation water demand is estimated at approximately 29 million m³/year, or about 17% of the original planned irrigation demand for rice cultivation. For wheat cultivation during the dry-season cropping period, annual irrigation water demand is approximately 84 million m³/year. These reductions release water that can be stored in Liyutan Reservoir, thereby improving public water security and increasing energy-system flexibility. Crop choice strongly affects the WEF outcome. If the converted area is allocated to wheat, the estimated wheat production is approximately 0.017 million tons/year. Although this accounts for only about 2% of Taiwan's net wheat food supply, it represents a food-security-oriented adjustment because wheat is almost entirely import-dependent. Unlike electricity-intensive greenhouse flower cultivation, wheat conversion does not introduce comparable electricity demand. Therefore, it provides a contrasting food-sector pathway: lower economic value than high-value flowers, but stronger food-security relevance and better preservation of system-level energy gains.

For flower cultivation, the energy implication depends strongly on the production system. Under the low-energy local flower pathway estimated from official agricultural energy-cost statistics, the additional electricity demand is approximately 17.9 million kWh/year, which is much smaller than the net energy gain of 175 million kWh/year achieved in Scenario D relative to Scenario B. This low-energy estimate represents local low-input flower production, including open-field cultivation or simple protected structures, rather than fully controlled greenhouse systems.

However, under a high-electricity greenhouse benchmark, electricity demand may increase to approximately 404.6 million kWh/year, exceeding the system-level net energy gain. Therefore, full conversion to electricity-intensive greenhouse flowers should not be interpreted as the recommended strategy. A mixed conversion strategy may be more appropriate: part of the area may be allocated to high-value flowers to support farmer income, while another part may be allocated to low-water-demand or food-security-oriented crops to preserve WEF benefits.

CONCLUSIONS

This study presents the Dajia–Daan River system as a practical WEF case linking public water supply, hydropower and pumped-storage operation, and agricultural irrigation. The results show that conservative high-storage operation may protect water supply in ordinary years but can suppress hydropower generation and reduce operational flexibility. Optimizing reservoir rule curves improves net energy performance while maintaining water-security constraints. Agricultural conversion in the selected irrigation district further reduces irrigation pressure and increases system flexibility. However, crop choice is critical. Low-water-demand or food-security-oriented crops such as wheat can preserve WEF

benefits, whereas full greenhouse flower cultivation may introduce enough electricity demand to offset energy gains.

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