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4th World Irrigation Forum

7-13 September 2025, Kuala Lumpur, Malaysia

Proceedings of the International Workshop on

Implementation of the Water-Energy-Food (WEF) Nexus for Building Resilience, Adaptation and Sustainable Socio-Economic Development

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"Implementation of the Water-Energy-Food (WEF) Nexus for Building Resilience, Adaptation and Sustainable Socio-Economic Development"

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Editor

Prof. Dr Ragab Ragab, President Hon. ICID and Chairman of the ICID Working Group on "Water-Energy-Food Nexus

Workshop Chairman

International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical, and not-for-profit Non-Governmental Organization (NGO). ICID, through its network of professionals spread across more than a hundred countries, has facilitated sharing of experiences and transfer of water management technology for over half-a-century. ICID supports capacity development, stimulates research and innovation, and strives to promote policies and programs to enhance sustainable development of irrigated agriculture through a comprehensive water management framework. The mission of ICID is to stimulate and promote the development and application of the arts, sciences and techniques of engineering, agriculture, economics, ecological and social sciences in managing water and land resources for irrigation, drainage, flood management, for achieving sustainable agriculture water management.

September 2025

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FORWARD

Prof. Dr. Ragab Ragab, Chairman of ICID WG WEF-NEXUS

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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 interdependencies 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. 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. Identifying and understanding such trade-offs, the WEF Nexus could be an efficient approach to sustainable socio-economic development. The Workshop will highlight the inter-relations of SDGs and how they are linked to the WEF Nexus. This aims to develop an inclusive and integrated governance framework that drives towards the realization of the SDGs. The sessions will also discuss the application of interactive modelling tools in basins of significant relevance. The Workshop will further focus on policy and governance mechanisms for implementing WEF solutions. The ICID's Working Group on Water Food Energy Nexus (WG-WFE_N) is organizing this International Workshop on "Implementation of the Water-Energy-Food (WEF) Nexus for Building Resilience, Adaptation and Sustainable Socio-Economic Development" during the 76th International Executive Council (IEC) Meeting and 4th World Irrigation Forum scheduled from 7-13 September 2025 at Kuala Lumpur, Malaysia. The WG-Nexus has organized a series of workshop started in ICID-Bali, Indonesia in 2019, then ICID - Adelaide, Australia in 2022, then Vizag-India in 2023 then Sydney, Australia in 2024.

Objectives

1. The current WEF Nexus models and frameworks, how they can inform decision-making, and how to implement the WEF Nexus innovations and solutions.
2. An inclusive and integrated framework towards the realization of the SDGs.
3. The application of trade-offs and tools to assess the WEF Nexus index in basins of significant international relevance to prioritize innovations.
4. Institutional and governance mechanisms to implement WEF solutions: WEF policy scenarios & Operationalizing WEF Nexus.
5. Solar irrigation within the WEF Nexus in agriculture. The focus will be on the examples of the application of the Nexus at different scales, the impact of Nexus application on Societies, Environment and Ecosystem and the impact of Climate Change on the WEF-Nexus.

A Decision Support System for Sustainable and Resilient Water-Energy-Food Management

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Ruchi Sharma, Navya Chandu1

ABSTRACT

The Water-Energy-Food (WEF) Nexus is increasingly recognized as a vital framework for addressing sustainability challenges, especially in regions facing growing pressure on natural resources and climate change. This paper introduces a Decision Support System (DSS) developed under the CGIAR Nexus Gains Initiative to support integrated WEF planning in India. The DSS integrates surface and groundwater models (SWAT+ and GWFLOW) with detailed land use and crop data to generate spatially explicit information on key hydrological and agricultural variables.

The DSS includes a WEF Scenario Generator and a WEF Trade-off Index (WEFTI) calculator, which allow users to explore different interventions such as expanding irrigated area, crop diversification, and improvements in irrigation efficiency and other scenarios while evaluating their implications across water, energy, food, and ecosystem. The tool has been applied in the Ganges River Basin, India to demonstrate how such a framework can support local and regional decision-making, helping to prioritize interventions that contribute to nexus gains and sustainable development goals. The WEF-Nexus DSS is useful in making policy decisions for improving cross-sectoral planning and resource management in complex and resource-constrained environments.

Keywords: WEF Nexus, Integrated Hydrological Modeling, Decision Support System, Trade-off Analysis, Climate Resilience, Sustainable Development Goals, Ganges River Basin.

INTRODUCTION

India stands at a critical juncture in managing its interdependent water, energy, and food (WEF) systems amidst escalating challenges posed by climate variability, resource overuse, and socio-economic transformation. With over 600 million people facing high to extreme water stress and agriculture consuming nearly 87% of the country's freshwater withdrawals (Ministry of Jal Shakti, 2023), the need for integrated policy and planning frameworks is more urgent than ever (Rakitskaya, 2021; Jain et al., 2023). Energy demands for groundwater extraction, food production, and water treatment are concurrently rising, intensifying the strain on already stressed systems (Barik et al., 2017). The traditional sectoral approaches to resource management are inadequate in capturing the trade-offs and synergies that exist within this nexus. Trade-off analyses are critical to food security strategies under climate stress (Ringler et al., 2010).

The WEF nexus approach offers a promising alternative by recognizing and quantifying the interactions among water, energy, and food sectors. It enables integrated resource planning to achieve co-benefits and minimize unintended consequences across systems. Effective access to, and management of water and energy resources are crucial for achieving sustainable agricultural development. Given the limited availability of arable land, increasing water stress, and unreliable energy supply, much of South Asian agriculture struggles to meet the demands of growing food for a rapidly expanding population. These challenges are further intensified by shifting lifestyles, dietary preferences, and food consumption patterns (Rasul, 2014). Stakeholder engagement and participatory modeling approaches have also been shown to enhance gendered decision-making (Magliocca, 2020). Tools like the Pardee-RAND WEF Nexus Index and the WEF Nexus Tool 2.0 provide quantitative indices to benchmark security status across sectors and scales (Mondal et al., 2023; Daher & Mohtar, 2015). Additionally, participatory approaches including gendered agent-based modeling and narrative-based Quantitative Storytelling (QST) bring a socio-institutional lens to nexus planning, essential in a diverse country like India (Magliocca, 2020).

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While a variety of models and methodologies have emerged globally, such as Integrated Assessment Models (IAMs), hydro-economic models, and multi-criteria decision analysis (Albrecht et al., 2018; Abdi et al., 2020; Kholod et al., 2021), most remain either conceptual or fragmented in their applications. There is a need for operational Decision Support Systems (DSS) for the WEF nexus, particularly tailored for countries like India. The WEFTI approach builds on existing composite index methodologies (Simpson et al., 2022) to provide a robust, comparative tool. These insights highlight the importance of integrated modeling frameworks like the WEF-Nexus DSS that go beyond sectoral silos to inform resilient investment planning

Therefore, we present in this paper a WEF-Nexus Decision Support System (DSS) tool, developed under the CGIAR Nexus Gains initiative.

Unlike existing models that often operate in disciplinary silos or lack spatially explicit hydrological integration, this DSS uniquely couples hydrological modeling (SWAT+ with GWFLOW) with district-level scenario planning tools and a newly developed Water-Energy-Food Trade-off Index (WEFTI). It is designed to spatially visualize trade-offs and synergies under various intervention scenarios across the Ganges Basin and beyond (Sena et al., 2024).

This integrated DSS framework incorporates three major innovations: (i) dynamic scenario generation aligned with current policies (e.g., irrigation efficiency, groundwater recharge, irrigated area expansion); (ii) spatial quantification of hydrological fluxes under Business-As-Usual (BAU) and intervention scenarios; and (iii) a user-friendly dashboard interface that allows district- or Hydrological Response Unit (HRU)-level decision-making support. Scenario outputs are visualized using comparative maps, radar charts, and computed WEFTI scores to enable coherence in policy dialogue.

The system enables multi-scale planning and supports informed decision-making for optimizing resource use, identifying policy trade-offs, and ensuring climate-resilient interventions.

In this paper, we detail the architecture, methodological integration, and components of the WEF-Nexus DSS, and illustrate its application in Indian basins with a focus on unleashing the spatial dimensions of the WEF index. We demonstrate how such a system bridges the gap between technical analysis and policy formulation, offering a transformative step forward for WEF nexus governance in India and other developing regions.

METHODOLOGY

The methodology for the WEF-Nexus Decision Support System (DSS) comprises an integrated and scalable framework that links hydrological modeling with policy-relevant scenario planning, geospatial visualization, and nexus index computation. A broader conceptual framework (Figure 1) modified from Carmona-Moreno et al. (2019) illustrates the pathway of evidence-driven policy engagement. This schematic consists of three interconnected components: evidence, nexus assessments, and policy dialogue.

- The "Evidence" block identifies key entry points for intervention: resource interdependencies and trade-offs, demand-supply imbalances, climate change impacts, and unsustainable agricultural and energy practices. These provide the empirical rationale for WEF-nexus engagement.
- The "NEXUS Assessments" phase involves modeling interlinkages across water, energy, and food systems using hydrological models (SWAT+ and GWFLOW), quantified metrics (WEFTI), and spatially explicit data layers. This middle block translates scientific insights into actionable knowledge.
- The "NEXUS Policy Dialogue" box represents the culmination of assessments in the form of scenario development. It feeds into a strategic policy framework for balancing trade-offs and designing investment plans and development measures. The DSS platform facilitates this step by enabling evidence-based dialogue among planners and stakeholders.

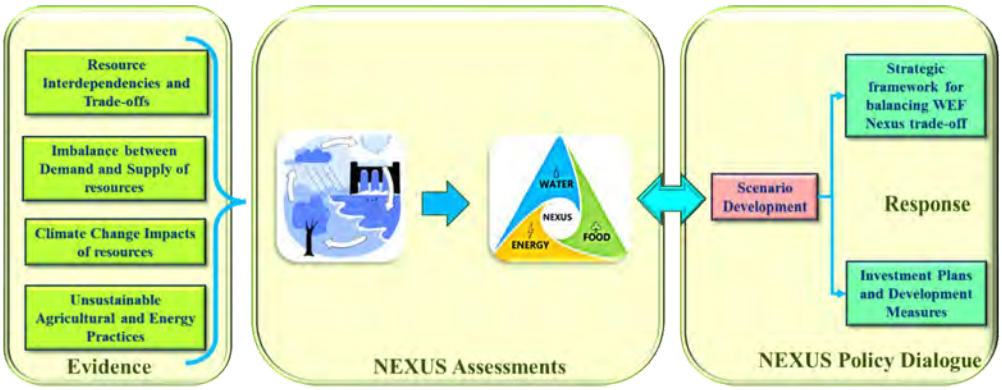


Figure 1. Conceptual pathway from evidence to WEF-Nexus policy dialogue and strategic responses. (Modified from Carmona-Moreno et al., 2019)

This overarching methodology underscores the DSS's ability not only to simulate resource dynamics but also to inform strategic responses by linking modeling evidence directly with policy development and investment planning.

The structure of the DSS, as depicted in Figure 2, builds upon the interaction of stressors, innovations, and outcomes, enabling coherence between diagnostics and decision-making (Sena et al., 2024).

Hydrological Modeling: SWAT+ Coupled with GWFLOW

The hydrological foundation of the DSS relies on the Soil and Water Assessment Tool Plus (SWAT+), which simulates the surface hydrology of watersheds, including processes such as rainfall-runoff transformation, evapotranspiration, infiltration, and water yield. This is integrated with the GWFLOW module to simulate groundwater dynamics and conjunctive use scenarios. Together, these coupled models enable a physically consistent representation of water balances at sub-basin and HRU levels. A baseline simulation under Business-As-Usual (BAU) conditions is calibrated using historic climate, land use, and irrigation data.

Outputs include surface runoff, percolation, lateral flow, groundwater recharge, and return flows, which are then aggregated spatially and temporally to visualize water availability, deficit areas, and sector-specific water use under changing management strategies.

Scenario Generator and Policy-Aligned Interventions

To inform decision-making, a scenario generation engine is incorporated within the DSS. This engine allows users to create multiple intervention scenarios by adjusting control parameters aligned with real-world policies. The currently supported scenarios include:

- Increasing Irrigation Efficiency (IIE): Reduces conveyance and application losses by adjusting irrigation efficiency coefficients.
- Increasing Groundwater Recharge (GWR): Simulates interventions like check dams, percolation tanks, or managed aquifer recharge to raise groundwater tables.
- Increasing Irrigated Area (IIA): Expands cultivated area with irrigation access, adjusting both water and energy demands.

Each scenario is evaluated against the BAU benchmark to assess changes in hydrological fluxes and resource consumption.

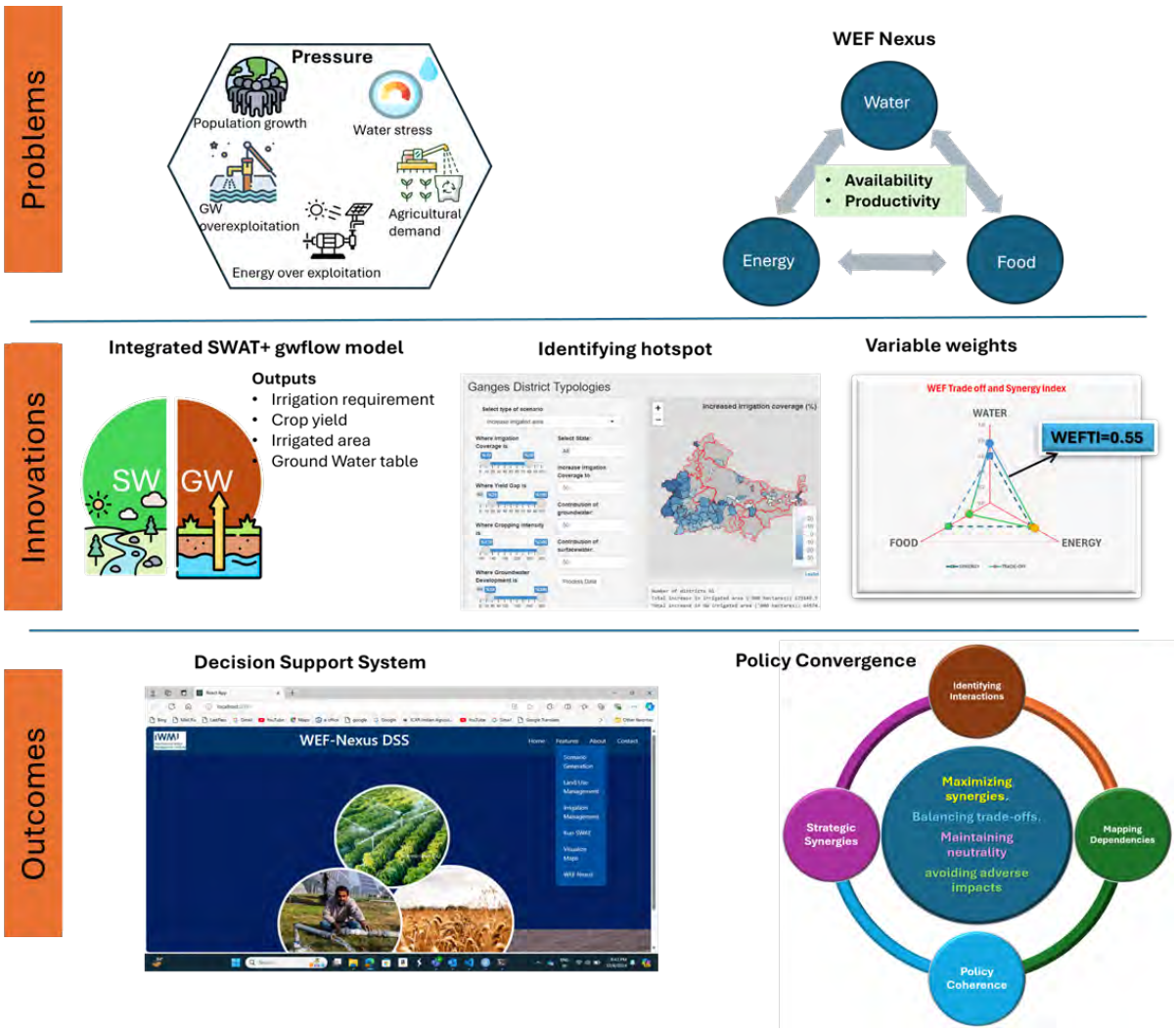


Fig. 2. Schematic of the WEF-Nexus DSS framework integrating stressors, innovations, and outcomes. (Source: Sena et al., 2024)

WEFTI: Water-Energy-Food Trade-off Index Computation

A key innovation of the DSS is the Water-Energy-Food Trade-off Index (WEFTI), which quantitatively captures the interaction of policy interventions across the three WEF dimensions. Tools such as the WEF Nexus Index can serve as benchmarking references for countries' performance across WEF dimensions (Simpson et al., 2022). The WEFTI is computed at the district level as a composite index using the following normalized indicators (Fig.3.):

- Water Use Efficiency: Ratio of beneficial water use to total water withdrawals.
- Energy Demand per Unit Output: Energy consumption normalized by agricultural output or irrigation volume.
- Food Production Change: Percent change in productivity or area under cultivation.

Each indicator is rescaled using min-max normalization and weighted based on stakeholder priorities or national targets. The net WEFTI score reflects cumulative trade-offs or synergies.

DSS Dashboard Functionality and Data Integration

The WEF-Nexus DSS is powered by an Excel- and R-based backend coupled with a user-centric graphical dashboard interface (Fig. 2). The dashboard includes the following functional modules:

- Scenario Configuration Panel: Allows users to define or adjust scenario parameters such as irrigation efficiency rates, land use types, recharge intervention locations, or cropping patterns.
- Data Upload and Pre-processing: Accepts model outputs and tabular inputs including hydrological fluxes, groundwater levels, cropping calendars, energy use, and irrigation infrastructure. The system supports spatially explicit data at HRU or district scales.
- Output Visualization Panel: Includes multi-layer interactive maps displaying model results (e.g., runoff, recharge, crop yield) for BAU and intervention scenarios. Maps use colour gradients and overlays to highlight critical differences.
- Trade-off Analytics Panel: Shows comparative radar charts and bar plots of WEFTI scores across districts under each scenario, allowing stakeholders to assess relative performance.
- Policy Coherence Support: Integrates outputs with decision pathways by linking outcomes to relevant Sustainable Development Goals (SDG) indicators, regional development plans, or resource allocation options.

All modules support real-time interaction, enabling users to compare scenarios, generate downloadable reports, and engage in evidence-based policy dialogues.

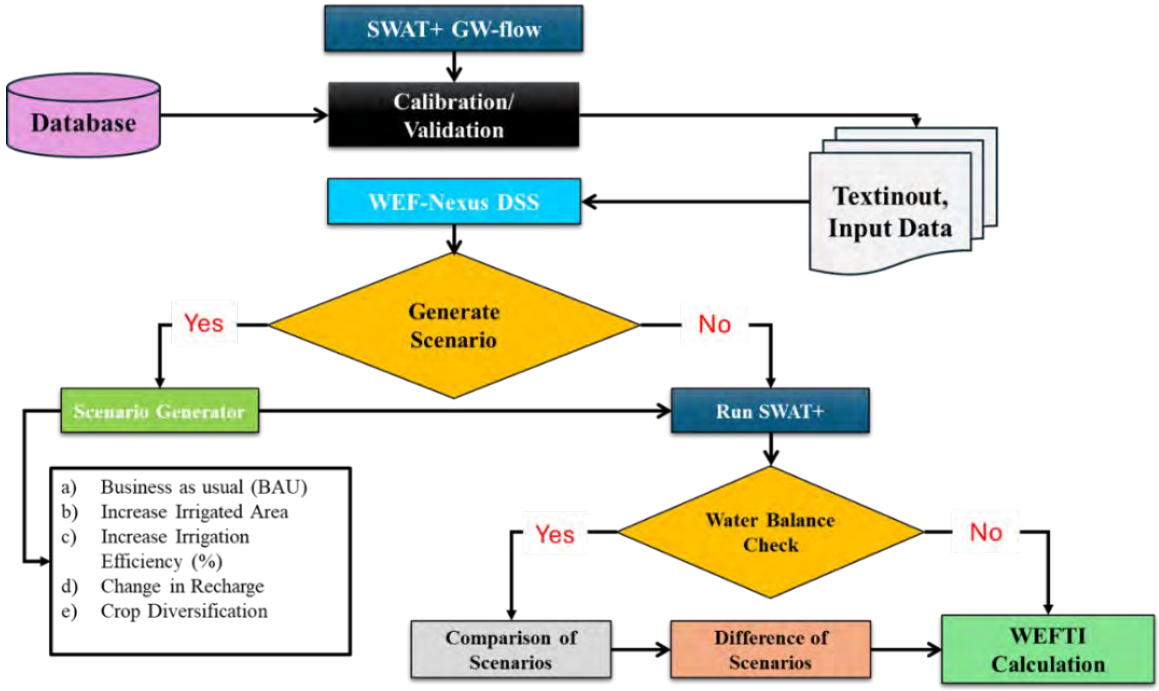


Fig. 3. Process flowchart leading to WEFTI estimation

Scalability and Model Independence

Designed for broad applicability, the DSS employs a modular and model-agnostic architecture. While SWAT+ and GWFLOW are the current engines for hydrological simulation, the dashboard can ingest outputs from other models. The back-end structure is flexible and can be expanded to other spatial domains or policy domains such as energy transitions or urban expansion.

Future versions aim to support additional scenario layers (e.g., climate change projections, solar irrigation potential), improved stakeholder input integration, and dynamic cloud-hosted deployment for multi-user access.
Together, these methodological components provide a robust, adaptable, and user-driven platform to support WEF nexus planning in complex and data-scarce environments.

RESULTS AND DISCUSSION

The WEF-Nexus DSS was applied in selected districts within the Ganges Basin to evaluate the impact of one key scenario: Increasing Irrigation Efficiency (IIE). This scenario was chosen based on prevailing challenges such as poor irrigation efficiency, and rising energy costs in agriculture. The results are visualized in the DSS dashboard using WEFTI radar charts and bar plots, providing an intuitive understanding of the sector.

Results of Increasing Irrigation Efficiency (IIE) Scenario

In this scenario (Fig. 4.), irrigation efficiency was increased by 20% in districts where groundwater development exceeds 75% and existing irrigation efficiency is below 60%. This targeted approach allowed for assessing water-energy-food trade-offs under stressed hydro-agricultural conditions.

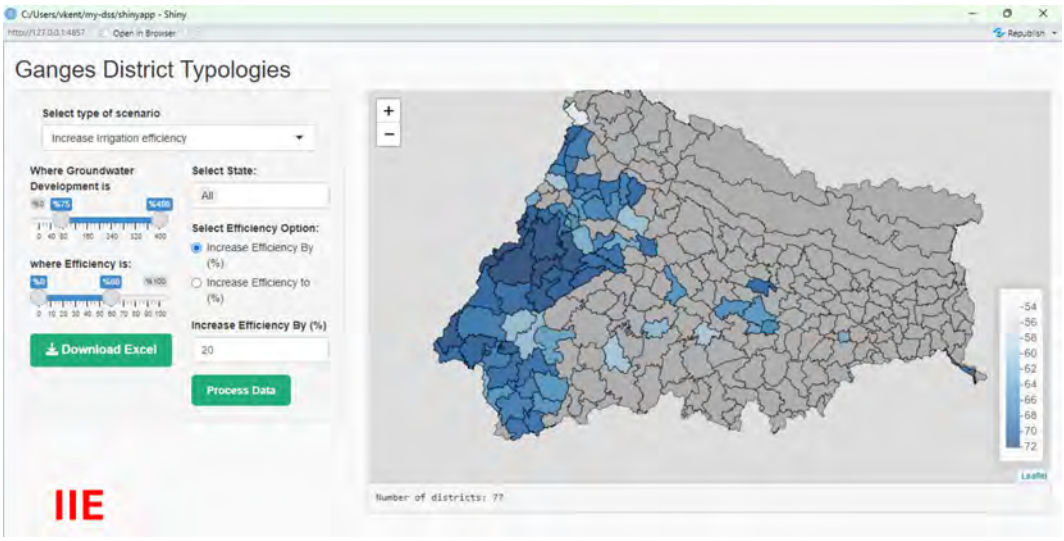


Fig. 4. Example representing irrigation efficiency scenario.

Figure 5(a) illustrates the district-wise relative gain in the Water-Energy-Food trade-off index (WEFTI) following a simulated 20% increase in irrigation efficiency (IE) to the selected districts that met the criteria for this intervention as defined in Fig. 4. The map shows that districts in the western and southwestern parts of the region experience notable gains, some exceeding 10%, reflecting the positive impact of improved IE in high-intervention zones. Moderate improvements (2.5% to 10%) are observed in several other central districts. This selective implementation underscores the importance of geographically targeted efficiency strategies to optimize WEF nexus outcomes where they are most needed and impactful.

Figure 5(b) presents a comparative radar plot analysis for three selected districts i.e. Hapur, Palwal, and Bulandshahr, highlighting sectoral gains in Water, Energy, and Food dimensions under a baseline (BAU) and an irrigation efficiency enhancement (IE) scenario.

The accompanying SDG indicators further link these sectoral gains to specific Sustainable Development Goals (SDGs).

- Palwal (Haryana): The most notable gain was in the energy sector [Fig. 5(b)], driven by reduced energy demand for groundwater pumping. Enhanced irrigation efficiency meant less water needed to be pumped, directly contributing to lower electricity or fuel consumption, thus advancing SDG 7 (Indicators 7.2.1 and 7.3.1).
- Hapur (Uttar Pradesh): Here, gains were concentrated in the water sector, where improved irrigation efficiency resulted in substantial water savings and improved availability for diverse uses. These gains directly supported SDG 6 (Indicators 6.4.1 and 6.4.2).
- Bulandshahr (Uttar Pradesh): The food sector saw a clear boost in productivity due to more effective water use. This improved crop yield and food security aligns with SDG 2 (Indicators 2.3.1 and 2.4.1).
- The radar charts demonstrate the comparative WEFTI gains across districts under IIE scenario versus Business-as-Usual (BAU). Bar plots for each district help to visualize the percentage gain in sectoral WEFTI contributions and support localized prioritization.

Trade-off and Synergy Analysis

The DSS's WEFTI outputs enabled visual and quantitative interpretation of cross-sector trade-offs. The radar charts and comparative bar plots revealed that improvements in one sector occasionally led to marginal declines in others, illustrating the importance of integrated planning. For example, maximizing food production without energy considerations could compromise groundwater sustainability and energy intensity.

These insights highlight the value of scenario-based trade-off analysis in identifying optimal and equitable interventions. As the DSS integrates these metrics into an interactive platform, it offers policymakers a transparent and scalable tool for balancing resource use while supporting India's SDG and Nationally Determined Contributions (NDC) commitments.

Implications for Sustainable Development Goals (SDGs)

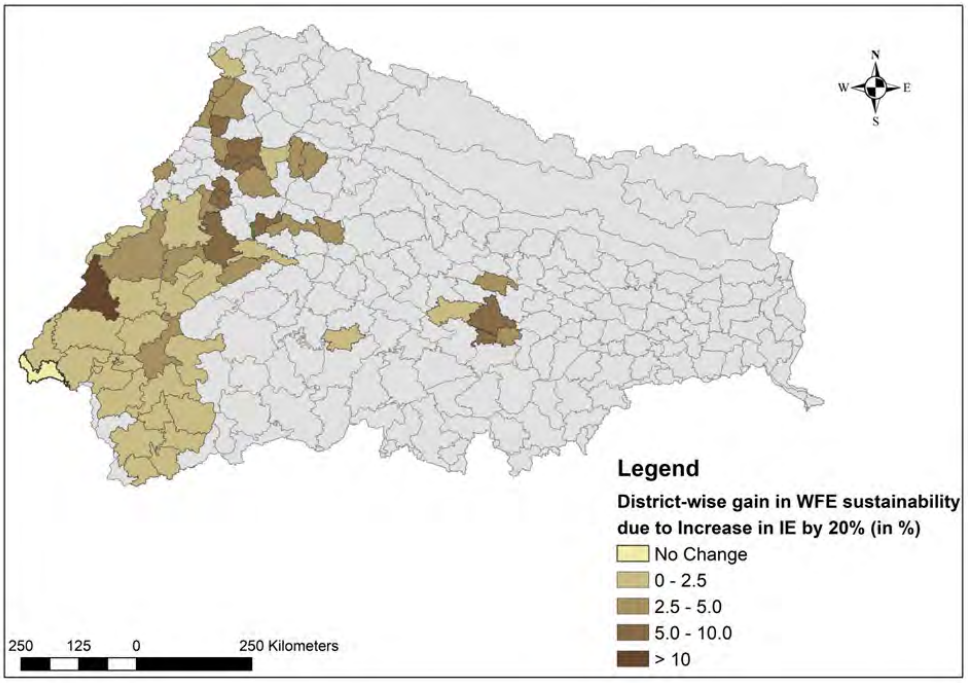
The outcomes of the scenario demonstrate that WEF-Nexus DSS can inform localized actions that have direct links to global development goals:

- SDG2 (Zero Hunger): through enhanced crop productivity and sustainable agriculture.
- SDG6 (Clean Water and Sanitation): via improved irrigation efficiency and groundwater sustainability.
- SDG7 (Affordable and Clean Energy): by reducing energy intensity in agricultural practices.

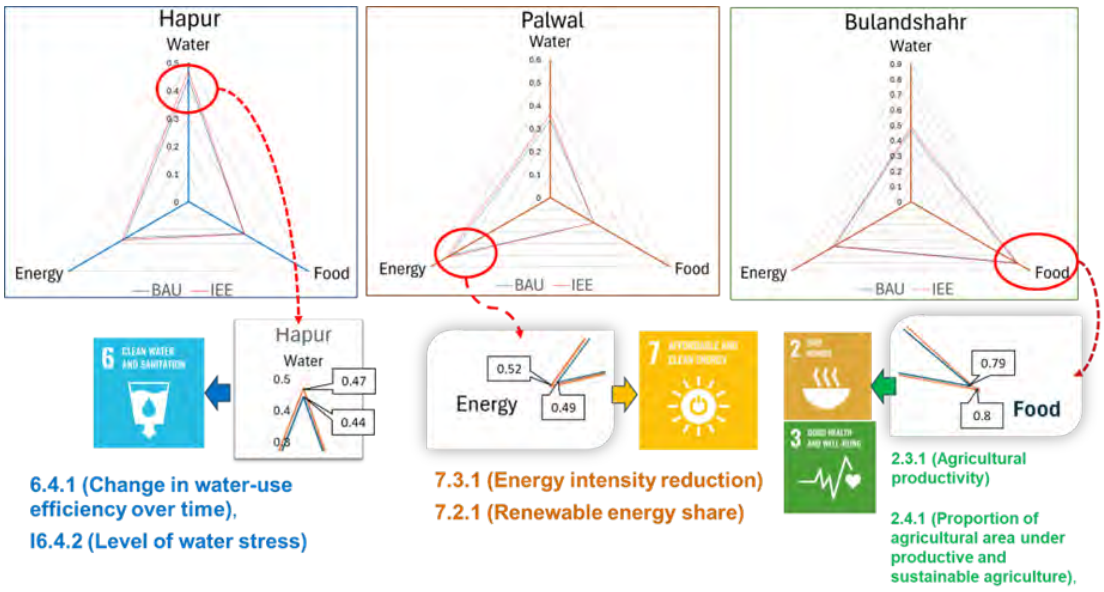
By enabling granular, district-wise decision-making and visualizing cross-sectoral impacts, the DSS facilitates a paradigm shift in agricultural water management, moving from isolated interventions to system-aware and policy-aligned strategies.

WAY FORWARD

Moving forward, the DSS's capabilities can be enhanced by integrating real-time data feeds from remote sensing platforms, extending the scenario generator to include climate resilience strategies (e.g., solar irrigation), and expanding spatial coverage to other vulnerable regions. Future development should also address current analytical gaps, including calibration frameworks, coupled socio-technical system models, and participatory co-design with stakeholders. Strengthening capacity at local levels and integrating feedback into the dashboard for adaptive planning are key to institutionalizing this innovation.



(a)



(b)

Fig. 5. Comparative gain in each sector as represented by WEF indices (a) represented quantities gain in WEF across districts due to an increase in efficiency by 20% (b) Illustrative examples of districts demonstrating sectoral advantages, highlighting their alignment with specific Sustainable Development Goals (SDGs).

CONCLUSIONS

An important step toward integrated, evidence-based resource planning in India has been taken with the development of the Water-Energy-Food (WEF) Nexus Decision Support System (DSS) under the CGIAR Nexus Gains Initiative. The DSS offers planners and policymakers a scalable, transparent, and operational platform for cross-sectoral analysis by combining the Water-Energy-Food Trade-off Index (WEFTI), spatial scenario simulation, and sophisticated hydrological modeling tools (SWAT+ and GWFLOW). The application of the DSS in the Ganges Basin has demonstrated its utility in identifying high-impact zones, informing irrigation efficiency improvements, and supporting equitable resource allocation. Moreover, the system's modular design ensures adaptability across geographies and sectors, making it suitable for replication in other regions facing complex resource challenges.

Decision-makers can prioritize interventions based on sustainability metrics and local needs thanks to its user-centric dashboard, which provides interactive visualization of resource flows, comparative scenario outcomes, and district-level trade-offs and synergies. The tool's relevance for national and sub-national policy integration is further increased by its capacity to match intervention strategies with Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDGs). As India confronts growing water stress, energy demands, and food security pressures under a changing climate, tools like the WEF-Nexus DSS offer a timely, science-policy interface to drive resilient development pathways. Moving forward, embedding the DSS in institutional planning processes and enhancing its participatory features will be key to mainstreaming the WEF nexus approach in India's sustainable development agenda.

REFERENCES

Abdi, H., Shahbazitabar, M., & Mohammadi-Ivatloo, B. (2020). Food, energy and water nexus: A brief review of definitions, research, and challenges. Inventions, 5(4), 56.https://doi.org/10.3390/inventions5040056

Albrecht, T.R., Crootof, A. and Scott, C.A., 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters, 13(4), p.043002.https://doi.org/10.1088/1748-9326/aaa9c6

Barik, B., Ghosh, S., Sahana, A. S., Pathak, A., & Sekhar, M. (2017). Water–food–energy nexus with changing agricultural scenarios in India during recent decades. Hydrology and Earth System Sciences, 21(6), 3041–3060. https://doi.org/10.5194/hess-21-3041-2017

Carmona-Moreno, C., Dondeynaz, C., & Biedler, M. (Eds.). (2019). Position paper on Water, Energy, Food and Ecosystems (WEFE) Nexus and sustainable development goals (SDGs). JRC Technical Report (JRC114177). Ispra, Italy: European Commission. https://doi.org/10.2760/5295

Daher, B. T., & Mohtar, R. H. (2015). Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water International, 40(5-6), 748–771. https://doi.org/10.1080/02508060.2015.1074148

Jain, S. K., Sikka, A. K. & , Alam, M. F (2023). Water-energy-food-ecosystem nexus in India—A review of relevant studies, policies, and programmes Frontiers in Water, 5, 1128198. https://doi.org/10.3389/frwa.2023.1128198

Kholod, N., M. Evans, Z. Khan, M. Hejazi, and V. Chaturvedi. Water-energy-food nexus in India: a critical review. Energy Clim Change 2: 100060. 2021. https://doi.org/10.1016/j.egycc.2021.100060

Magliocca, Nicholas R. "Agent-based modeling for integrating human behavior into the food–energy–water nexus." Land 9, no. 12 (2020): 519. https://doi.org/10.3390/land9120519.

Villamor, Grace B. "Gender and water-energy-food nexus in the rural highlands of Ethiopia: where are the trade-offs?." Land 12, no. 3 (2023): 585. https://doi.org/10.3390/land12030585

Ministry of Jal Shakti. (2023, March 23). Ensuring optimum utilization of water in agriculture sector (Press Release ID: 1910078). Press Information Bureau, Government of India. https://www.pib.gov.in/PressReleasePage.aspx?PRID=1910078

Mondal, K., Tantuway, R. B., Chatterjee, C., & Singh, R. (2023). Development of a water-energy-food nexus model for multiscale studies. Irrigation and Drainage, 72(5), 1356-1373. https://doi.org/10.1002/ird.2800

Rakitskaya, Katsiaryna. "Water-energy-food nexus in India: a review of interlinkages and challenges for a sustainable development." (2021). https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Auu%3Adiva-453235

Rasul, Golam. "Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region☆." Environmental Science & Policy 39 (2014): 35-48.https://doi.org/10.1016/j.envsci.2014.01.010

Ringler, Claudia, Tingju Zhu, Ximing Cai, Jawoo Koo, and Dingbao Wang. (2010) "Climate change impacts on food security in sub-Saharan Africa." Insights from comprehensive climate change scenarios 2 (2010). https://hdl.handle.net/10568/153659

Sena, D. R., Alam, M. F., Chaudhary, S., Chandu, N., Behera, A., Sharma, R., Sikka, A., McCartney, M., & Hafeez, M. (2024). WEF-Nexus Decision Support System (DSS): A sustainability and resilience tool for India. Colombo, Sri Lanka: International Water Management Institute (IWMI), CGIAR Initiative on NEXUS Gains. https://hdl.handle.net/10568/173157

Simpson, G.B., Jewitt, G.P., Becker, W., Badenhorst, J., Masia, S., Neves, A.R., Rovira, P. and Pascual, V., (2022). The water-energy-food nexus index: a tool to support integrated resource planning, management and security. Frontiers in Water, 4, p.825854.https://doi.org/10.3389/frwa.2022.825854

Towards A Holistic and Coherent Governance Framework for The Water-Energy-Food Sectors: A South African Perspective

Luxon Nhamo[1], Sylvester Mpandeli[2], Stanley Liphadzi[3], and Tafadzwanashe Mabhaudhi[4]

ABSTRACT

The security of water, energy and food is a key priority at the global level as the three resources are currently stressed due to the recurrence of extreme weather events, depletion, degradation and increasing demand from a growing population. The severe insecurity levels of the three calls for interventions through systematic and transformative approaches that are capable of guiding holistic transformation. However, the transition from the current linear model to a circular economy is impeded by the lack of a harmonised and holistic governance framework. This study reviewed the water-energy-food (WEF) nexus governance and institutional arrangements in South Africa, including policies, strategies, plans, programmes and institutions. All relevant governance frameworks and documents related to water, energy, food security and environmental sustainability were considered. The aim was to guide the formulation of a harmonised and cross-sectoral management governance framework to guide the operationalisation of the WEF nexus. The lack of such a framework has slowed the realisation of the Sustainable Development Goals, SDGs. A harmonised and holistic WEF governance framework is essential to promoting a balance in resource use and management, as it is a pathway towards meeting socio-economic targets, achieving human and environmental health, and meeting SDGs.

Keywords: Water productivity; water management; food security; irrigation potential; landuse policy

1. INTRODUCTION

Water, energy and food are intricately interconnected as energy generation requires water in large volumes for food production, mining, hydropower and power plant cooling (Javan et al., 2023). On the other hand, energy is also needed for pumping, treating and distributing water and for collecting, treating and discharging wastewater (Hamawand, 2023). Simultaneously, water and energy are needed for food production, while crops such as maize, soybean and sugarcane are now being found to have alternative uses as biofuels (Gerbens-Leenes et al., 2009). These mutual interconnections are referred to as the water-energy-food (WEF) nexus (Leck et al., 2015). Formally published evidence of the three-way mutual interactions among the WEF sectors only started in 2008 (Hellegers et al., 2008). It has since grown into a topical subject due to its capabilities to guide the transition from a linear to a circular economy (Nhamo et al., 2024). The linear economy promotes sector-based resource management, resulting in optimal efficiencies in those sectors at the detriment of other equally important and interlinked sectors, whereas the circular economy is transformative and cross-sectoral, allowing resources to remain in use for a long possible time (Nhamo et al., 2024). Today, the WEF nexus has grown into a leading discourse framework, conceptual model and analytical tool that is key to sustainable development as the world acknowledges the need for holistic management of resources (Mpandeli et al., 2022). The WEF nexus has since gained traction and more research from 2015 after the enactment of the SDGs, as it is strongly linked to sustainable development (Mabhaudhi et al., 2021). The SDGs are framed in a way that all seventeen Goals are linked to water, energy and food (McCollum et al., 2017). However, the main limiting factor to adopting the WEF nexus and realising the SDGs has been the lack of a harmonised governance framework to guide holistic policy decisions (Naidoo et al., 2021). A WEF nexus governance framework is a supporting policy tool that guides the management and compliance of interconnected resources to enhance security and sustainability and drives integrated compliant operations (Pahl-Wostl, 2019).

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South Africa has some well-written policy documents, but these remain sectoral and lack harmonisation with interlinked sectors (Naidoo et al., 2021). These governance frameworks have different meanings in policy development, which slows the transition from the linear to the circular economy and the much-needed integrated resource management (Rogge and Reichardt, 2016). This is besides the fact that the WEF nexus has evolved from a theoretical and conceptual framework to an analytical model capable of guiding a holistic and integrated management of the three interconnected resources (Mehta et al., 2024). For example, a WEF nexus integrative analytical decision support tool was developed and applied in South Africa (Nhamo et al., 2020a), indicating how the country's three WEF resources are managed, and showing areas in need for immediate intervention. The model was further successfully applied at the local level (Nhamo et al., 2020b), then at the southern African regional scale (Mabhaudhi et al., 2019) and was also applied to assess progress towards (SDGs) (Mabhaudhi et al., 2021). Besides the evidence on the role of the WEF nexus in guiding sustainable development, operationalisation and adoption of the approach has been slow due to the lack of a policy framework to guide implementations (Farmandeh et al., 2024). As a result, and besides the evident risks, it has been business as usual, further compounding existing challenges.

Continued sectoral management of resources is exacerbating the country's risk and vulnerability. The challenges of resource insecurity are compounded by climate change, which manifests through increased frequency and intensity of extreme weather events (drought, flooding and heatwaves) (Amoah and Simatele, 2021). Extreme weather events are also causing the emergence of novel infectious diseases and resource degradation and depletion, exacerbated by the increasing demand for resources from a growing population (Nhamo and Ndlela, 2021). The risk and vulnerability to resource insecurity are expected to persist as long as resources are managed from a sector perspective (Davis and Vincent, 2017). Therefore, securing WEF resources is a priority for South Africa as they form the foundation of sustainable development. Recent studies have provided empirical evidence and demonstrated the transformative and integrated ability of the WEF nexus in guiding strategic decisions on holistic resource management (Taguta et al., 2023). The models have become an integral part of resource management and sustainable development as they provide quantitative relationships between the WEF sectors and identify areas for priority interventions (Nhamo et al., 2020a).

As a transformative approach, the WEF nexus can integrate strategies aimed at guiding cross-sectoral interventions to address challenges brought about by population growth, rural-urban migration, urbanisation, increased consumption demands and climate change (Mpandeli et al., 2018). Such holistic and multicentric interventions result in multiple efficiencies that eliminate duplication and inefficiencies in resource allocation and utilisation (Botai et al., 2021). This is further enhanced by streamlining developmental programmes and synergies and trade-offs are identified promptly to optimise resource use efficiency. However, to achieve this, a total transformation in the governance structures is required to guide the needed transition towards a circular economy and sustainable development. The study, therefore, assesses WEF nexus-related policies, plans and programmes in the context of South Africa. The focus is to analyse policy documents related to water, energy, and food and propose a holistic and coherent governance framework.

2. THE SYSTEMATIC REVIEW PROCESS

This study used a multidisciplinary approach and a systematic literature review to address specific research questions, including: (a) what are the existing water, energy and food governance structures and institutions in South Africa? (b) how do the existing governance structures relate to each other? and (c) what strategies that can be undertaken to harmonise sector-based governance structure? These questions are answered in Sections 3.1, 3.2 and 4 respectively, Section 4 being the practical example or empirical evidence. The process guided the development of a coherency governance framework to drive the harmonisation of sector-based policies. The aim was to harmonise policy and guide holistic, cross-sectoral and integrated resource management towards sustainable development. A harmonised policy framework is a driver for the implementation of the WEF nexus and a catalyst to achieve the SDGs (Nhamo et al., 2025).

The systematic literature review was critical for selecting literature that included WEF sector policies, frameworks, and strategies, among other publications of significance to resource governance in South Africa. Major literature search engines that include Google Scholar, Scopus, Mendeley and Web of Science were used to search terms like "water policies", "energy policies", "food policies", "WEF resources in South Africa", "agriculture policies", "policy coherence", "policy harmonisation", "integrated resource management",

"sustainable development", "WEF nexus and SDGs", "SDGs governance frameworks", "interlinkages among SDGs" and "WEF nexus prospects on realising the SDG targets". The search yielded both peer-reviewed and grey literature, resulting in a hundred and forty-five retrieved articles. The number was reduced to fifty-five articles that were eventually considered relevant to the study's objectives and answered the research questions. Figure. 1 is a flowchart showing the literature selection criteria and the screening procedure, which yielded n = 145 documents, and after a thorough screening, n = 90 articles were excluded. This resulted in n = 55 articles being considered for the analysis.

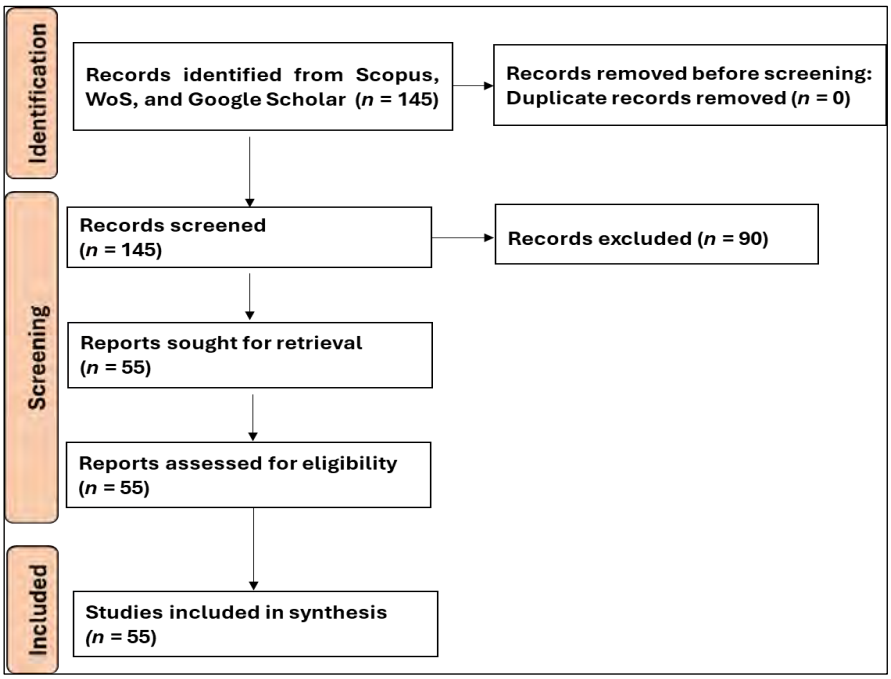

Figure 1. Graphic representation of processes followed during the literature search, handling, and screening.

The second part of the study included the application of the integrative WEF nexus model using South Africa as a case study, assessing how WEF resources are managed and governed (Nhamo et al., 2020a). The case used an interval of five years between 2015 and 2020, a reasonable period to assess and appreciate any changes and progress in resources management and governance. The integrative analytical model uses the Analytical Hierarch Process (AHP) and, a Multi-criteria Decision Making (MCDM) process developed by Saaty (Saaty, 2008). The model holistically assesses WEF resources management and governance through the pairwise comparison matrix (PCM) to develop quantitative relational composite indices.

3. RESULTS AND DISCUSSION

3.1. Selected WEF Sectors Related Policies

The Constitution of South Africa (RSA, 1996) is the overarching policy document that guides all legal and policy instruments in the country. The right to water is enshrined in the Constitution and implemented through different statutes framed around the Constitution. The Constitution is clear on sufficient access to sufficient water, food, and energy by all. It informed the formulation of the National Water Act, Energy Act and The White Paper on Agriculture, among others (Table 1). National legislative frameworks are also informed by international and regional agreements. While South Africa has good legislative and policy instruments that guide the management of WEF sectors, the country still has a long way to go in integrating these frameworks. Integrating policy frameworks for interlinked sectors is a priority as current challenges cut across all sectors and, therefore, require cross-sectoral interventions to guide the transition from the current linear approach to a circular model. The WEF nexus provides pathways that guide the equitable distribution of resources and achieve sustainable development.

Through a spider web graph, the indices then establish quantitative relationships in the management of WEF resources.

Table 1. Main policy and legal frameworks governing WEF sectors in South Africa

Water sector	Energy sector	Agriculture (food) sector
National Water Act 36 of 1998, with the Amendment Bill (2023)	The National Energy Act (2008)	Agricultural Policy in South Africa (1998)
National Environmental Management Act 107 of 1998	White paper on energy policy (1998)	Agriculture and Agro-processing Master Plan (AAMP) (2022)
National Water Resource Strategy 3 (2013)	White paper on renewable energy (2003)	White paper on agriculture (1995)
White Paper on a National Water Policy for South Africa	Integrated Energy Plan (IEP, 2003 and 2005)	Integrated resource plan (IRP, 2011)
Water for Growth and Development Framework	Integrated resource plan (IRP, 2019)	Strategic Agriculture Sector Plan

3.2. Empirical evidence of resources management: Case of South Africa

An overview of the current status of WEF resources governance and management in 2015 and 2020 in South Africa is given in Table 2 (WorldBank, 2024). The data were used in an integrative analytical WEF nexus model (Nhamo et al., 2020a), which applies the Analytic Hierarchy Process (AHP) and, a multi-criteria decision method (MCDM) (Saaty, 1977). The AHP was used to establish the pairwise comparison matrix (PCM), normalisation of the indices and providing the numerical relationships between the distinct indicators (Nhamo et al., 2020a). The model, which is applicable at any spatial scale, assessed resource management in 2015 and 2020 and the results are key to assessing progress in achieving the SDGs over time. The approach simplifies the human understanding of the interconnectedness of interlinked sectors, facilitates easy interpretation of the complex relationships between the WEF sectors and guides policy decisions on holistic priority interventions (Naidoo et al., 2021).

Table 2. State of the WEF resources indicators for South Africa in 2015 and 2020

Sector	**Indicator and short name**	**Indicator status**		
		2015	2020	Units
Water	Proportion of available freshwater resources per capita (availability)	821.3	821.4	m3
	Proportion of crops/energy produced per unit of water used (productivity)	26.2	26.2	$/m3
Energy	Proportion of population with access to electricity (accessibility)	85.5	84.4	%
	Energy intensity measured in terms of primary energy and GDP (productivity)	8.7	8.7	MJ/GDP
Food	Prevalence of moderate/severe food insecurity in the population (self-sufficiency)	5.7	6.2	%
	Proportion of sustainable agricultural production per unit area (productivity)	3.5	5.6	kg/ha

Source: World Bank (2024)

The PCM and the normalisation of the indices generated the composite indices for the two reference years (Table 3). A five-year interval was selected in this case as it is a reasonable period where resource management and governance changes can be appreciated. The composite indices represent the quantitative relationships between the WEF sectors; however, the relationship is difficult to interpret and understand when shown in a table format. The quantitative relationships are then represented through a spider web graph (Figure. 2), vividly illustrating how resources are related and managed. The WEF nexus integrated index is a weighted average of the composite indices that indicate the level of the country's resource management.

Table 3. WEF resources security composite indices for South Africa in 2015 and 2020

Indicator	**Composite indices**	
	2015	2020
Water availability	0.126	0.099
Water productivity	0.128	0.221
Energy accessibility	0.141	0.079
Energy productivity	0.111	0.199
Food self-sufficiency	0.314	0.292
Cereal productivity	0.180	0.111
WEF integrated index	0.203	0.155

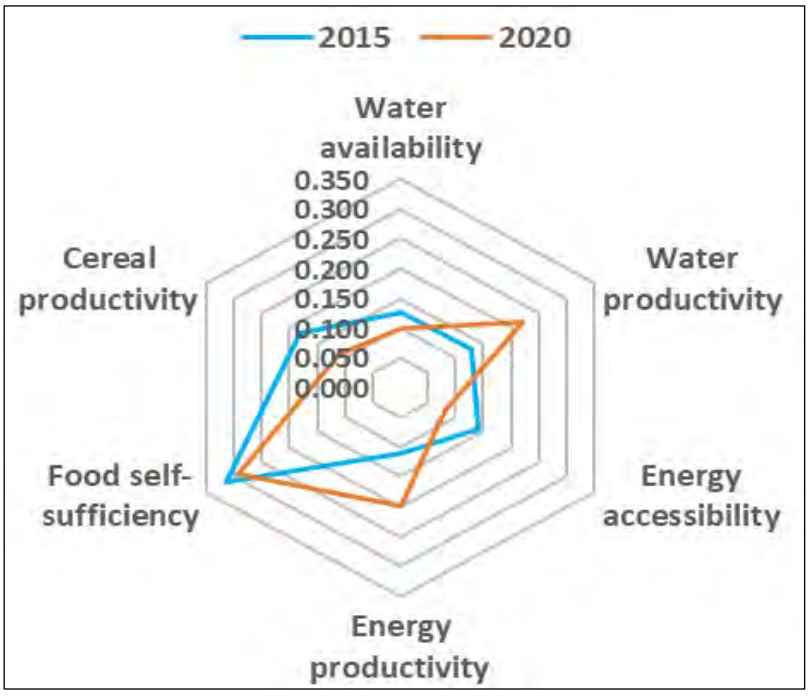

Figure 2. Changes in WEF resources management in South Africa (2015 and 2020)

The composite indices (Table 3 and Figure. 2) are dimensionless and range between 0 and 1. The spider web graph, therefore, quantitatively relates WEF nexus indicators in terms of management (Nhamo et al., 2020a). For example, the water availability indicator is related to other indicators by 0.126 in 2015, which decreased to 0.099 in 2020. However, an indicator of 1 represents the best possible resource management, and 0 represents poor management. The blue represents how the resources where being managed in 2015 and the orange line represents the management in 2020. For example, in 2015 the water productivity indicator was low because of drought in the country which resulted in much emphasis given to water saving. This resulted

in improved water productivity in 2020. But this improvement was at the expense of the other equally important indicators like energy accessibility as the country had severe energy insecurity resulting in load shedding. Cereal productivity also decreased because of drought and the country had to important the stapple maize.

The centrepieces are irregular in shape; an indicator of linear and sector-based governance systems still being pursued. The centrepieces should be circular to indicate balanced resource management indicating a clear path towards sustainability. Therefore, the shape of the centrepieces gives a synopsis of the state of resource management and governance and the economic model being pursued. Sector-based and linear models in resource management only compound current cross-cutting challenges. The shape of the centrepieces is key to indicating priority areas for priority intervention from a cross-sectoral and holistic perspective. Therefore, the key to the spider web diagram is to identify trade-offs and synergies for timely intervention. The shape of the centrepieces shows areas needing either to mitigate trade-offs or maximise synergies. The changes between the two reference years indicate the model is also essential for assessing progress towards achieving the SDGs (Mabhaudhi et al., 2021).

The integrative analytical WEF nexus model is, therefore, a decision-support tool for assessing the state of resource management and governance at any given time and at any spatial scale. The model has been used at the local scale (Nhamo et al., 2020b), national scale (Nhamo et al., 2020a) and regional scale (Mabhaudhi et al., 2019). The approach provides pathways to (a) enhance holistic, sustainable, and resource use efficiency of the WEF resources, (b) promote equitable and balanced resource management and distribution, (c) ensure human and environmental health, and (d) support the provision of ecosystem services. These attributes make the WEF nexus an essential systems approach to assess resource management. However, besides the current evidence of the importance of the WEF nexus, its implementation has been hindered by the lack of an integrated, harmonised and holistic governance framework.

4. TOWARDS WEF SECTORS POLICY COHERENCE

The management of WEF resources is at the heart of human well-being, poverty reduction and sustainable development (FAO, 2014). The three essential sectors are extremely sensitive to climate change and these tenets are enshrined in South Africa's Constitution and the National Development Plan (NDP). The demand for water, energy and food is set to increase owing to the projected population growth, migration and urbanisation, economic development, international trade, and improved standards of living. The insecurity of the three resources is exacerbated by climate change and continued degradation and depletion, and sector-based and linear approaches are still being pursued (Nhamo et al., 2025). The increasing competition for these resources is resulting in negative impacts on the country's socio-economic security as the country continues with the current linear model to manage resources instead of the recommended circular model as demonstrated by the imbalanced management of resource (Figure 2) (Nhamo et al., 2020a). While it is important to understand the interlinkages between the WEF sectors, it is also important to know the transformative approaches capable of solving the current grand challenges that cut across sectors. However, as shown by the literature review, the lack of a harmonised policy framework and institutions that recognise the interconnectedness of WEF resources is resulting in the duplication of resource allocation and exacerbating existing challenges (Rasul and Neupane, 2021). This lack of alignment, coherence and synergy among the sector policies is hindering the operationalisation of the WEF nexus as there is no framework to drive the approach.

Therefore, there is still a gap in policy coherence to facilitate the management of resources from a holistic and integrated perspective. This is a process that begins with extensive stakeholder engagement to allow a buy-in from everyone from the start. This buy-in will allow all stakeholders to take ownership and catalyse the harmonisation of the current sector-based WEF governance structures. Thus, policy harmonisation accelerates the transition from the current linear to the circular model and catalyses progress towards achieving SDGs (Nhamo et al., 2024, 2025).

Figure 3 is a proposed stepwise transformative framework towards a holistic and coherent governance instrument to achieve resource security and sustainable development. A holistic governance framework guides policy and decision-makers to inclusively meet national targets, including the SDGs and NDP goals. Four main interlinked themes are proposed to guide the formulation of a harmonised WEF sectors governance framework that facilitates the transitional change, stimulates resource use efficiency, provides the pathways towards

sustainable development and achieves the desired outcomes. These themes include (a) the drivers of change including environmental and societal drivers which combine to trigger resource insecurity, (b) risk and vulnerability and the capacity to adapt which attract the need for cross-sectoral interventions, (c) preparedness and risk reduction initiatives that allow the development of integrated models to overcome barriers and drive informed actions that lead to sustainability, and (d) the resilience and adaptation building pathways that guide strategic policy decisions (Figure 3). The sub-themes explain the main themes to facilitate an understanding the challenges and pave the way towards policy coherence. An understanding of these processes catalysed the transdisciplinary actions to advance the operationalisation of the WEF nexus as guided by a harmonised and cross-sectoral policy framework. This is key to integrated realisation of multiple SDGs and eventually resource security.

The framework highlights the need to address socio-ecological drivers through multicentric interventions that require circular and transformative approaches like the WEF nexus that guide concurrent and timely responses to current cross-cutting challenges. However, the entire process requires transdisciplinary actions and interventions to formulate a coherent and effective harmonised governance framework for the WEF nexus operationalisation (Naidoo et al., 2021). Without policy coherence, as it is now, sectors will continue with the business as usual, exacerbating the current challenges. Research and development should focus on advancing integrated planning and policy convergence and demonstrate the benefits to policy-makers, highlighting the disadvantages of sector-based policies in resource management. WEF nexus models have recently been developed to monitor and evaluate the WEF resources planning and management (Nhamo et al., 2020a). WEF nexus integrative model identifies synergies and trade-offs. Once adopted and with the backing of a holistic governance framework, the WEF nexus has the potential to catalyse the optimal allocation of resources and the promotion of inclusive and sustainable national economic growth and development.

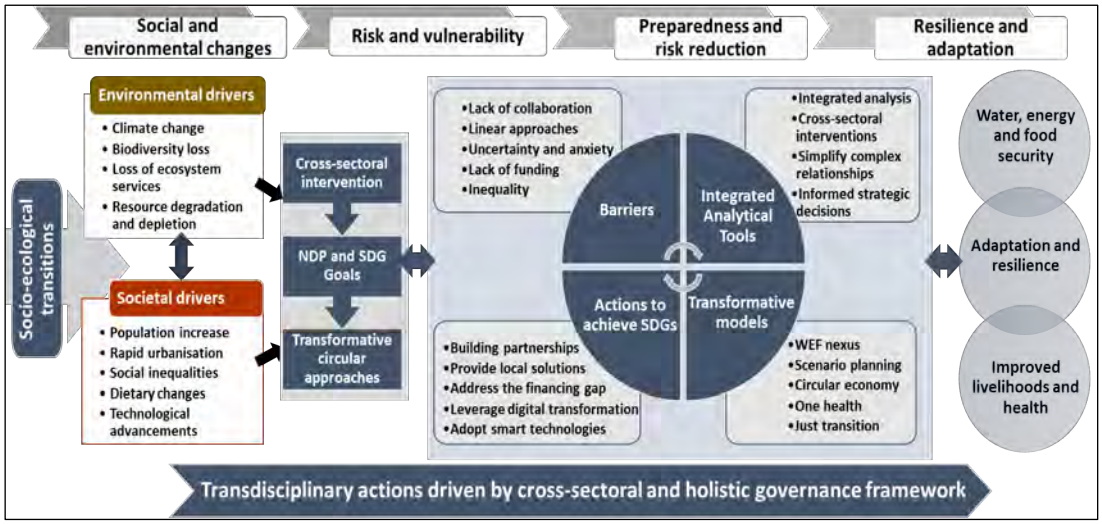

Figure 3. A stepwise process that drives the formulation of a harmonised WEF sectors governance framework. This nexus-based governance framework is driven by transformative, cross-sectoral, and holistic approaches adapted for South Africa. The framework outlines the multisectoral, multicentric, transdisciplinary, and integrated process and actions that lead to resilience and adaptation.

5. RECOMMENDATIONS

Considering the interlinkages between WEF sectors and the impact of climate change on resources, there is a need for a coherent governance framework to facilitate policy harmonisation, coordination and management of resources. The current linear approach in managing resources results in optimal efficiencies in preferred sectors at the expense of equally important resources. The presence of a harmonised WEF nexus governance framework guides integrated resource development and management and identifies cross-sectoral synergies and trade-offs for timely intervention. The South African case study (Section 3.2) has highlighted that the WEF nexus approach offers opportunities for policy-makers to sustainably meet set targets, including achieving SDGs (Nhamo et al., 2025). Advancing integrated planning, policy coherence and management is critical for

raising inter-sectoral awareness about the WEF nexus. Efforts should focus on eliminating barriers that include lack of collaboration, fragmented and sector-based policies, uncertainty and anxiety among key stakeholders and inequality. These are the major challenges hindering the implementation of the WEF nexus. The following recommendations are proposed for successful operationalisation of the WEF nexus:

Evidence from the case study has shown that at the level of governance, it is necessary to ensure that horizontal linkages exist during the design and implementation phases of the WEF nexus model. It is also important that policies on water, energy, food and climate are harmonised and coordinated to guide a sustainable transition from the current linear approaches to the circular model. The WEF nexus, therefore, provides opportunities to stabilise competing demands in an environment of scarce resources by ensuring that development in one sector has minimal impacts on the other sectors.

As the SDGs are meant to be achieved by 2030, there is not much progress made towards meeting the set targets within the set period. The WEF nexus is meant to drive and catalyse the SDGs, yet adoption of the concept has been slow. The low implementation of the WEF nexus is due to the lack of a harmonised WEF nexus governance structure that would function as a driver and catalyst of the approach.

Energy insecurity in South Africa has contributed to the country's credit status being downgraded. The 'crises' in the energy sector have also led to the 'explosion' of new coal mines. This has raised renewed fears of acid mine drainage and conflicts with water and agriculture sectors as mining pollutes water and competes for land with agriculture. While energy might receive more attention as an important economic driver, it must be noted that many of the pressures that drive energy demand also apply to water and agriculture. Therefore, water, energy and food are all central to South Africa's vision of delivering a better quality of life to its citizens. This highlights the urgent need for better convergence of policy amongst the three sectors.

As an initiative to start the WEF nexus discussions, there is a need for an inter-sectoral dialogue that also includes all stakeholders and forms a Community of Practice at the national level. The platform should be used to promote WEF nexus research and harmonisation of policies.

6. CONCLUSIONS

Results from this literature review indicate that while there is a clear understanding of the role of water, energy and agriculture in South Africa, existing sector-based governance frameworks framed along the principles of the linear economic model are exacerbating the current challenges of resource insecurity and national vulnerabilities. The empirical evidence of the WEF nexus integrative analytical model applied in South Africa indicates the pursuance of the linear model, showing minimal transition towards the circular economic model. This has resulted in an unbalanced economy and sector-based resource management, resulting in disharmony in resource allocation and suboptimal efficiencies in selected sectors at the expense of equally important resources as indicated by Figure 2. This has resulted in a disjointed economic development, compounded by resource degradation and depletion and aggravation of existing cross-cutting challenges. Therefore, cross-cutting challenges require cross-sectoral interventions and a transition from the current linear model to the circular economy. The literature review and the case study informed the development of an integrated WEF sectors governance framework to drive the formulation of a harmonised WEF policy to guide the cross-sectoral management of resources. The developed framework provides an excellent platform for policy convergence and augments integrated resource management from a transformative perspective. In this context, policymakers need to champion nexus planning as there is enough evidence on the role of the WEF nexus in driving towards sustainable development. However, there is currently a lack of a holistic policy framework to guide WEF nexus operationalisation. This has seen meeting the SDGs targets being elusive.

REFERENCES

Amoah, L.N.A., Simatele, M.D. (2021) Food security and coping strategies of rural household livelihoods to climate change in the eastern cape of South Africa. Frontiers in Sustainable Food Systems 5, 692185.

Botai, J.O., Botai, C.M., Ncongwane, K.P., Mpandeli, S., Nhamo, L., Masinde, M., Adeola, A.M., Mengistu, M.G., Tazvinga, H., Murambadoro, M.D. (2021) A review of the water–energy–food nexus research in Africa. Sustainability 13, 1762.

Davis, C.L., Vincent, K., (2017) Climate risk and vulnerability: A handbook for Southern Africa, 2nd ed. Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa, p. 202.

FAO, (2014) The water-energy-food nexus: A new approach in support of food security and sustainable agriculture, in: Dubois, O., Faurès, J.-M., Felix, E., Flammini, A., Hoogeveen, J., Pluschke, L., Puri, M., Ünver, O. (Eds.). Food and Agriculture Organization (FAO), Rome, Italy.

Farmandeh, E., Choobchian, S., Karami, S. (2024) Conducting water-energy-food nexus studies: what, why, and how. Scientific Reports 14, 27310.

Gerbens-Leenes, W., Hoekstra, A.Y., van der Meer, T.H. (2009) The water footprint of bioenergy. Proceedings of the National Academy of Sciences 106, 10219-10223.

Hamawand, I., (2023) Energy Consumption in Water/Wastewater Treatment Industry—Optimisation Potentials. MDPI, p. 2433.

Hellegers, P., Zilberman, D., Steduto, P., McCornick, P. (2008) Interactions between water, energy, food and environment: evolving perspectives and policy issues. Water Policy 10, 1-10.

Javan, K., Altaee, A., BaniHashemi, S., Darestani, M., Zhou, J., Pignatta, G. (2023) A review of interconnected challenges in the water–energy–food nexus: Urban pollution perspective towards sustainable development. Science of the total environment, 169319.

Leck, H., Conway, D., Bradshaw, M., Rees, J. (2015) Tracing the water–energy–food nexus: Description, theory and practice. Geography Compass 9, 445-460.

Mabhaudhi, T., Nhamo, L., Chibarabada, T.P., Mabaya, G., Mpandeli, S., Liphadzi, S., Senzanje, A., Naidoo, D., Modi, A.T., Chivenge, P.P. (2021) Assessing Progress towards Sustainable Development Goals through Nexus Planning. Water 13, 1321.

Mabhaudhi, T., Nhamo, L., Mpandeli, S., Nhemachena, C., Senzanje, A., Sobratee, N., Chivenge, P.P., Slotow, R., Naidoo, D., Liphadzi, S. (2019) The Water–Energy–Food Nexus as a Tool to Transform Rural Livelihoods and Well-Being in Southern Africa. International journal of environmental research and public health 16, 2970.

McCollum, D., Gomez Echeverri, L., Riahi, K., Parkinson, S., (2017) SDG7: Ensure access to affordable, reliable, sustainable and modern energy for all. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, p. 47.

Mehta, K., Shah, M.J., Zörner, W. (2024) Agri-PV (Agrivoltaics) in Developing Countries: Advancing Sustainable Farming to Address the Water–Energy–Food Nexus. Energies 17, 4440.

Mpandeli, S., Naidoo, D., Mabhaudhi, T., Nhemachena, C., Nhamo, L., Liphadzi, S., Hlahla, S., Modi, A. (2018) Climate change adaptation through the water-energy-food nexus in southern Africa. International journal of environmental research and public health 15, 2306.

Mpandeli, S., Nhamo, L., Senzanje, A., Jewitt, G., Modi, A., Massawe, F., Mabhaudhi, T., (2022) The water–energy–food nexus: its transition into a transformative approach, Water-Energy-Food Nexus Narratives and Resource Securities. Elsevier, Amsterdam, Netherlands, pp. 1-13.

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., Slotow, R., Jacobson, M., Modi, A., Mabhaudhi, T. (2021) Operationalising the water-energy-food nexus through the theory of change. Renewable and sustainable energy reviews 149, 10.

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S., Modi, A.T. (2020a) An integrative analytical model for the water-energy-food nexus: South Africa case study. Environmental Science and Policy 109, 15-24.

Nhamo, L., Mpandeli, S., Liphadzi, S., Mabhaudhi, T., (2024) Understanding circularity and transformative approaches and their role in achieving sustainability, Circular and Transformative Economy. CRC Press, Boca Raton, Florida, USA, pp. 1-8.

Nhamo, L., Mpandeli, S., Liphadzi, S., Mabhaudhi, T. (2025) Catalysing Sustainable Development Goals through the water-energy-food nexus. iScience, 30.

Nhamo, L., Ndlela, B. (2021) Nexus planning as a pathway towards sustainable environmental and human health post-Covid-19. Environment Research 110376, 7.

Nhamo, L., Ndlela, B., Mpandeli, S., Mabhaudhi, T. (2020b) The Water-Energy-Food Nexus as an Adaptation Strategy for Achieving Sustainable Livelihoods at a Local Level. Sustainability 12, 8582.

Pahl-Wostl, C. (2019) Governance of the water-energy-food security nexus: A multi-level coordination challenge. Environmental Science & Policy 92, 356-367.

Rasul, G., Neupane, N. (2021) Improving policy coordination across the water, energy, and food, sectors in South Asia: a framework. Frontiers in Sustainable Food Systems 5, 602475.

Rogge, K.S., Reichardt, K. (2016) Policy mixes for sustainability transitions: An extended concept and framework for analysis. Research Policy 45, 1620-1635.

Saaty, T.L. (1977) A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 15, 234-281.

Saaty, T.L. (2008) Decision making with the analytic hierarchy process. International journal of services sciences 1, 83-98.

Taguta, C., Nhamo, L., Kiala, Z., Bangira, T., Dirwai, T.L., Senzanje, A., Makurira, H., Jewitt, G.P., Mpandeli, S., Mabhaudhi, T. (2023) A geospatial web-based integrative analytical tool for the water-energy-food nexus: the iWEF 1.0. Frontiers in Water 5, 1305373.

WorldBank, (2024) World Bank Indicators. World Bank Group (WB), Washington DC.

Food-Water-Energy-Ecosystem, WEFE Nexus in the Souss-Massa River Basin, Morocco

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ABSTRACT

The Souss-Massa River Basin in Morocco faces growing pressures on its water, energy, and agricultural resources due to climate change, population growth, and intensive farming. This study adopts the Nexus approach (Water-Energy-Food-Ecosystem) to analyse interdependencies and propose sustainable management strategies for these resources in the Basin. The basin suffers from water scarcity, with overexploited coastal aquifers and declining rainfall, while agricultural demand particularly for irrigation drives high energy consumption, mainly from fossil fuels. Despite Morocco's shift to solar-powered irrigation with desalinated sea water, groundwater depletion continues, worsened by pollution and seawater intrusion and subsequent salinization. Meanwhile, ecosystems like the UNESCO-listed Arganeraie forest are degrading due to deforestation and unsustainable land use and land use change. The study identifies key challenges, including fragmented governance, lack of inter-sectoral coordination, and outdated policies. It evaluates international best practices and proposes strategic interventions including integrated governance shifting from sectoral "silos" to Nexus-based planning, renewable energy expansion through solar-PV integration with desalination plants and pumped-storage hydropower, sustainable agriculture promoting drip irrigation, agroforestry, and terracing to reduce erosion on highlands, ecosystem restoration protecting the Arganeraie through reforestation and regulated land use, and circular economy promoting agricultural waste use for bioenergy and organic fertilizers. The findings emphasize urgent reforms in policy, technology, and stakeholder collaboration to balance socio-economic growth with resource sustainability. This study provides a framework for Nexus-driven resilience in arid basins, offering actionable insights for Morocco and similar regions.

Keywords: Water-Energy-Food Nexus, Souss-Massa Basin, Climate Resilience, Water Scarcity, Sustainable Agriculture, Renewable Energy, Integrated Governance.

1. INTRODUCTION

Water, energy, soil and food are fundamental to any economy, yet their resources are increasingly scarce and degraded worldwide. These sectors are deeply interconnected, necessitating integrated policies the core idea behind the NEXUS approach, which seeks synergies for sustainable growth and long-time maintenance. Over the past twenty years, the Water-Energy-Food (WEF) nexus concept has attracted considerable interest in both academic research and policy development (Suleiman and Shahid 2023). Various methodologies have been introduced to support its practical application. Extensive reviews of nexus assessment methods have been conducted by Albrecht et al. (2018) and Ramos et al. (2020).

Souss Massa River Basin is located in mid-western Morocco, along the Atlantic coast (Figure 1), and covers an area of 29,300 km², accounting for 4.5% of Morocco's total area. It has a population of 2.9 million (HCP, 2024), with 58% residing in urban areas. The region's economy relies primarily on three key sectors: agriculture, fishing, and tourism (Ministry of Interior-Morocco, 2015). Approximately 175,500 hectares of land are devoted to cultivating cereals, citrus fruits, almonds, and vegetables (MAPM, 2017). The region supplies 85% of Morocco's vegetables and over half of its exported citrus, employing nearly 50% of the local workforce in agriculture (Choukr-Allah et al., 2017). Alongside tourism and fishing, agriculture contributes 6.6% to Morocco's GDP (Kingdom of Morocco High Commission for Planning, HCP,2024).

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Figure 1. Souss-Massa River Basin: locations of aquifers and dam reservoirs

Water resources are vital for nearly all socio-economic activities in Souss-Massa. Irrigation accounts for 86% of total water demand, with the rest allocated to industry, tourism, and domestic use (ABHSM -PDAIRE, 2023). The basin has faced water stress since the 1970s, exacerbated by climate change. Overexploitation of the Souss and Chtouka aquifers has led to severe groundwater depletion, with deficits of 292 million cubic meters (Mm^3) / y and 63 Mm^3/y, respectively. Groundwater aquifers meet roughly 60% of the annual demand, estimated at 625 Mm^3/y, exceeding natural recharge by an average of 200 Mm^3 yearly (ABHSM-PDAIRE, 2023). However, overexploitation and low annual rainfall (~200 mm in the plains) to recharge these aquifers have caused severe aquifer depletion. For instance, the Souss aquifer—the basin's primary source has seen water tables drop by 15–30 meters over the past 40 years, at a rate of 0.5–2.5 meters annually (Brahim, 2016). This decline has triggered seawater intrusion and subsequent soil salinization, increasing pumping costs and compromising the water supply security (Moha et al., 2017).

Intensive farming, especially citrus and greenhouse crops (Vegetables and Berries), consumes 93% of water in the basin. Moreover, state subsidies for energy supply of butane compressed gas (used in pumping) have indirectly encouraged groundwater overuse. Data from the Directorate of Energy and Mines in Souss-Massa reveals that butane consumption for pumping reached 84,000 tons in 2019. Recent estimates indicate that 20% of groundwater pumping is powered by butane-driven pumps, while Solar Photovoltaic (PV) systems account for 10%, and the remaining 70% rely on electricity from the national grid (based on consultations with local energy experts and the Regional Office for Agricultural Development, ORMVA, in Souss-Massa).

The region boasts a unique natural ecosystem of significant ecological importance, characterized by rich biodiversity and high levels of endemism. The argan tree serves as the principal species, dominating these ecosystems (covering 64%, or 868,000 hectares). These ecosystems play a vital environmental and socioeconomic role. The Arganeraie Biosphere Reserve, recognized by UNESCO, helps promote their development and conservation. Additionally, the forests act as a source of soil carbon sequestration and natural shield, protecting the agricultural lands from wind erosion impacts and desertification. Several industries have emerged around this ecosystem, including argan oil production, aromatic and medicinal plant

cultivation, beekeeping, and cactus farming. Deforestation, overgrazing, and soil erosion threaten the argan forest, and contribute to ecosystem degradation.

Given the growing strain on water resources in the Souss-Massa basin, fragmented governance in water management risks worsening scarcity through unsustainable overexploitation. This underscores the urgent need to move away from the traditional "silo" approach that has long shaped water, energy, and agricultural policies. Instead, adopting the integrated Nexus approach is a critical strategy designed to reduce harmful non-cross-sectoral impacts while enhancing synergies for more sustainable and efficient resource management.

This study applied the NEXUS approach to assess the interconnected management of water, energy, food, and ecosystem (WEAE) in the Souss-Massa Basin. By analyzing theoretical frameworks and their practical implementation, the research evaluated the potential benefits of the WEFE Nexus for resource-scarce basins, a common challenge across Morocco. The study's originality lies in its foundation on sectoral stakeholders' perceptions of climate change, informed by meteorological data models and future climate scenarios.

The research aimed to provide comprehensive insights into the Souss-Massa basin by: mapping natural resources (water, energy, arable land, ecosystems) and their vulnerabilities under climate change pressures; assessing current and projected demands on these resources; evaluating interactions between water, energy, agriculture, and ecosystems; analysing policy coherence across sectoral strategies (water, energy, agriculture, environment); and proposing strategic recommendations through a roadmap to optimize NEXUS linkages, guiding policymakers in decision-making and public policy formulation.

2. METHODS

2.1 Study area and stakeholder engagement

This study focused on the Souss-Massa basin, drawing from technical reports, surveys, and datasets provided by regional and national organizations overseeing water, agriculture, energy, and environmental management. Plenary meetings were conducted with key institutions, including Hydraulic Basin Agency (ABHSM), Directorate of Water Research and Planning (DRPE), Directorate of Hydraulic Development (DAH), Regional Office for Agricultural Development (ORMVA), Division of Rural Affairs (DRA), National Office of Electricity and Drinking Water (ONEE), National Institute of Agronomic Research (INRA, 2021a,b), and Water and Forests Department.

These discussions aimed to understand regional development plans, identify sectoral interdependencies, and gather stakeholder perspectives on climate adaptation and resource management.

2.2 Nexus assessment methodology

The study applied the NEXUS approach to assess the interconnected management of water, energy, agriculture/food, and ecosystems in the Souss-Massa Basin. The research methodologies involved mapping natural resources and their vulnerabilities, assessing current and projected demands, evaluating sectoral interactions, and analysing policy coherence across water, energy, agriculture/food, and environmental strategies.

3. RESULTS AND DISCUSSION

3.1 Climate change impacts on water resources in Souss-Massa Basin

The trends of annual precipitation in the basin have declined by 15–30% since the 1970s, with the driest years (e.g., 2019–2020) recording <100 mm precipitation in the coastal areas (ABHSM, 2019; Driouech et al., 2020) and last year (2024) there was only 99 mm rainfall which is less than half of a normal year. Future projections indicate that under RCP4.5 and RCP8.5 scenarios, models predict a 20–40% reduction in rainfall by 2080 (Gommes et al., 2009) and increased frequency of multi-year droughts, similar to the 1994–2005 period when dam reservoirs operated at <30% capacity (Seif-Ennasr et al., 2016) and less than 20% during the year 2023.

In terms of hydrological impacts, Wadi flows could decrease by 35–50% by 2050, reducing surface water availability (ABHSM, 2019), and groundwater recharge by 12–36%, worsening aquifer depletion (IPCC, 2014).

The Souss-Massa region, particularly around Agadir, has experienced significant warming over recent decades. Between 1971 and 2017, Agadir's average temperature rose by 1.7°C (DMN, 2019), exceeding global averages. Summer maxima now surpass 46°C, e.g., in Amskroud, a small town at the outskirts of Agadir, in 2011, leading to increased forest fires (e.g., 960 hectares burnt in 2013 in the Souss region) (DREFLCDSO, 2018), and heat stress on crops, particularly citrus and tomatoes, which are highly sensitive to temperature fluctuations.

Under different emission scenarios (RCP4.5 and RCP8.5), the region faces a temperature rise by 2100; under moderate scenario (RCP4.5): between 1–4°C increase, and under high-emission scenario (RCP8.5): 4–6°C increase (ABHSM, 2019). The potential evapotranspiration may rise by 20% by 2050 (Seif-Ennasr, 2019) which means greater water loss from soils, increasing irrigation demands.

This trend will affect crop productivity, since the Souss-Massa region is Morocco's agricultural hub, producing 70% of the country's citrus and 60% of its tomatoes (FAO, 2020). Climate impacts include shortened crop cycles, with tomatoes and citrus growth periods shrinking by 8–18% (AGRHYMET, 2020), reducing yields, and earlier maturation leading to lower fruit quality (e.g., smaller citrus sizes, reduced sugar content).

By 2050, water needs for key crops (citrus, tomatoes, bananas) could rise by 15–25% (FAO, 2018), and groundwater depletion associated to seawater intrusion will be more critical, as the aquifers are already overexploited, with some areas experiencing 4–5 meters/year groundwater level decline (ABHSM, 2020).

3.2 Dam siltation and compound risks

The Souss-Massa region currently has nine dams with a total storage capacity of 740 million m³ (Table 1). However, due to an annual siltation rate of 5.4 million m³, their capacity is projected to decline to 556 million m³ by 2050. The basin loses 400–600 tons/km²/year of soil due to deforestation and overgrazing (El Mouden, 2017). In the case of the Youssef Ben Tachfine Dam, siltation reduced capacity by 0.4 Mm³/year (MBHSM-PDAIRE, 2023); and for the Abdelmoumen Dam, 30% of storage capacity was lost since 1985 (ORMVASM, 2019). This has an economic cost; as siltation diminishes reservoir lifespans, requiring $5/m³ for dredging (World Bank, 2016).

Table 1 Storage capacity of Dams in the Souss Massa River Basin (24/06/2025)

Dam name	Storage Capacity Million m^3	Actual Volume stored Million m^3	Actual filling % of capacity
Prince Moulay Abdellah	90.6	39.5	43.6
Sidi Abdellah	10.4	7.3	69.7
Abelmoumen	198.4	5.1	2.6
Imi El Kheng	9.8	1.4	14.5
Youssef Ben Tachfine	298.2	42.0	14.6
Ahl Souss	4.7	0.7	15.9
Aoulouz	89.0	40.4	45.4
Moukhtar Soussi	39.8	4.2	10.6
Dkhila	0.2	0.2	76.0
Total	740.8	140.6	19.0

The Souss-Chtouka aquifer is impacted by seawater intrusion and the influence of Triassic formations in the southern High Atlas. Coastal urbanization, tourism, and excessive groundwater extraction have worsened the decline in water tables, leading to an up-coning effect and the mixing of saltwater with freshwater. Studies classify the Chtouka-Massa aquifer as one of the most severely affected by salt intrusion. The Chtouka-Massa aquifer shows elevated chloride (Cl^-) concentrations because saltwater intrusion due to over pumping has salinized 20 km² of the Chtouka aquifer (Ez-zaouy et al., 2025). Also, extreme rainfall events (e.g., 2014 floods) caused $150 million in damages (DGPR, 2015).

3.3 Policy and governance challenges

Morocco has adopted laws and strategies to address these challenges, including Law 36-15 promoting integrated water management, Green Morocco Plan (PMV) focusing on agricultural modernization and water efficiency, and National Water Plan (2020–2050) prioritizing desalination, wastewater reuse, and drip irrigation system. However, enforcement remains weak, with unchecked well drilling and non-compliance with groundwater abstraction contracts.

Law 36-15 on water establishes Integrated Water Resources Management (IWRM) at the basin level (Article 1), requires metering of all wells and imposes fines for illegal drilling (up to 100,000 Moroccan Dirham) (Articles 80–82), and creates Basin Councils (e.g., Souss-Massa) to oversee water allocation (Decree 2.18.768, 2019). However, implementation remains weak, even though a great effort has been made by the river basin agency of Souss-Massa, discouraging conservation (World Bank, 2020).

The Green Morocco Plan targeted water efficiency by converting 550,000 ha to drip irrigation system nationwide between 2008 and 2020, achieved 90% in Souss-Massa) (MAPM, 2021) and subsidizing 70% of drip system costs for small farmers (up to 30,000 MAD (Moroccan Dirham currency)/ha) (ADA, 2019). The outcomes include reducing water use by 30–50% in modernized farms (ORMVASM, 2020). However, this goal could not be reached.

The 2007 Souss Aquifer Contract aimed to reduce pumping by 30%, but withdrawals increased by 15% (2010–2020) due to lack of monitoring (ABHSM, 2021). Only 5% of farms comply with metering requirements (CRI-SM, 2020). Three regional agencies manage water/agriculture (ABHSM, ORMVASM, ONEE), leading to overlapping mandates (World Bank, 2019).

Butane subsidies cost $2 billion/year nationally, with 33% diverted to agricultural pumping (IMF, 2021) and farmers pay 0.4 MAD/kWh for pumping vs. real cost of 1.2 MAD/kWh (MEMEE, 2022).

3.4 Energy-water-agriculture/food nexus analysis

The nexus is a new concept of managing resources through integration. Very few studies are reported on the nexus in the Arab and African countries and are cited by Al-Zubari et al. (2018). Al-Zubari et al. (2018) indicated Water-Energy-Food nexus has become the centre of global policy, development and research in order to meet the ever-increasing demand for water, energy and food in resource limited countries. Recently Aliewi and Alomirah (2020) have recommended an integration of good agricultural practices for better water productivity, improved water efficiency, and land management for food trade.

Within the context of the study area, the agricultural pumping consumes approximately 33% of national butane subsidies. The energy mix for groundwater extraction comprises: 70% electricity from national grid, 20% butane-powered pumps, and 10% solar photovoltaic systems. Solar energy potential reaches 2,154 kWh/m²/year in the region. Pilot installations of 500 solar pumps (25 kW each) demonstrate annual savings of 1.2 MWh per farm. The recently completed Chtouka desalination plant (400,000 m³/day capacity) requires hybrid solar-wind integration to reduce energy costs by 40%.

The Souss-Massa Regional Council signed a 2 million MAD agreement with the Moroccan Agency for Energy Efficiency (AMEE), allocating 1.2 million MAD to wind energy projects. Key actions include installing two wind measurement stations in rural municipalities (Tamri, Agadir Ida Outanane Province and Ait Wafka Tiznit Province), conducting energy audits for public buildings, and training renewable energy installers and service providers across the region. Fig. 2 shows the Integrated agriculture/food-water-energy-ecosystem nexus model for Souss-Massa, including a waste-to-energy plant in Greater Agadir using pyrolysis cogeneration (capacity: 290,000 tons/year), alongside a local pyrolyzer manufacturing unit, support for an electric vehicle charging infrastructure producer, and energy optimization solutions for Ibn Zohr University, including renewable energy integration studies (SEI, 2017).

Solar Energy Developments within the region include a photovoltaic plant in Foum Lahcen (Tata Province), pending completion of the larger Noor Tata project in Akka Ighen (Günay et al., 2018) and IRESEN-supported R&D projects concerning PROPRE.MA (National photovoltaic production mapping) and solar thermal

performance study at the Ait Baha cement plant (partnering Ciments du Maroc and Ibn Zohr University) (Souss-Massa Regional Council, 2017).

3.5 Ecosystem services and restoration

The Arganeraie forest covers 868,000 ha (64% of basin area) but experiences annual losses of 600 ha due to deforestation and encroachment. Forest restoration efforts target 500 ha/year replanting, with Payment for Ecosystem Services securing $385,000 for 3,650 ha conservation. Agroforestry systems demonstrate 60% soil erosion reduction compared to monocultures. Terraced agroforestry reduces soil loss by 60% vs. monocultures, with target of 10,000 ha of argan/olive intercrops by 2030.

Souss-Massa National Park shows 50% of 40,000 ha degraded by pollution. Wastewater reuse potential of 48 Mm³/year by 2050 could irrigate 770 ha of green belts (ABHSM-PDAIRE, 2023).

3.6 The nexus approach implementation

The Souss-Massa basin stands as an example of why integrated Nexus-based management is essential for balancing water security, agricultural productivity, energy sustainability, and ecosystem health (Fig. 2). The basin's severe water stress (only 671 Mm³/year of renewable surface water, ABHSM-PDAIRE, 2023), overexploited aquifers (very high extraction rates in Souss-Chtouka), and climate vulnerability (projected 40% rainfall decline by 2080) demand a systemic approach that breaks down sectoral silos.

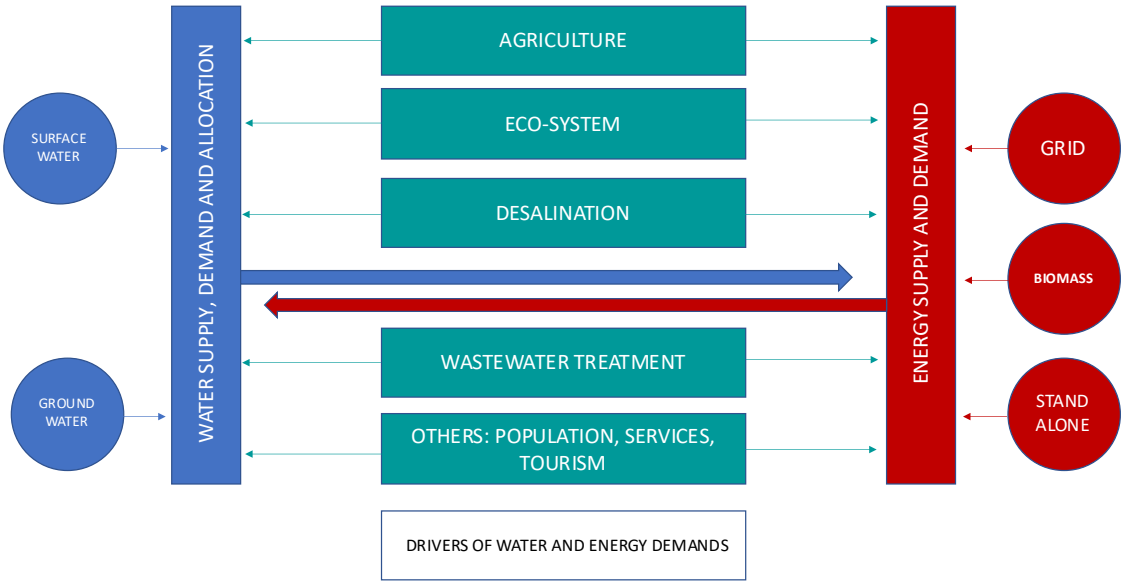

Figure 2. The Nexus model for Souss-Massa Basin: resource allocation, sectoral demands, and energy supply options in Souss-Massa Basin.

Agriculture consumes 86% of water and 33% of butane subsidies for pumping, yet drip irrigation and solar energy could reduce groundwater dependence by 30%. The Chtouka desalination plant (400,000 m³/day) must integrate solar/wind hybrids to avoid 40% higher energy costs. Reforesting 500 ha/year of argan forest could increase groundwater recharge by 5–10%. Wetland restoration requires treated wastewater reuse (48 Mm³/year potential) to sustain biodiversity.

4. STRATEGIC RECOMMENDATIONS FOR NEXUS SOLUTIONS

Based on our study and the data collected from ABHSM Nexus results, the following strategic recommendations emerged from the analysis for the Souss-Massa Basin:

- For the Irrigation Sector Industry, the following actions will allow to save 48 million cubic meters of water per year:
- Converting 42,000 hectares to micro-irrigation systems.
- Limiting groundwater pumping in irrigated areas of the Souss Basin to match the renewable volumes, with remaining deficit/demand met by seawater desalination.
- Large-scale promotion and incentives for high-value crops, supported by annual indicators (climate data, crop rotation, market trends) for farmers.
- Adoption of high-efficiency irrigation technologies (e.g., continuous irrigation, nanotechnology) to reduce water use and boost productivity.
- Encouraging substitution of water-intensive crops with less demanding alternatives.
- Establishing a direct link canal between Abdelmoumen Dam and Dkhila Dam to improve water supply distribution efficiency and reduce losses.

For the drinking purposes the following actions will allow to save 9 million cubic meters of water per year:

- Improve the efficiency rate of distribution networks to reach 80% by 2030 and 85% from 2040 onward, maintaining this rate through 2050.
- Renewal of networks, service connections, and meters.
- Detection and repair of leaks, along with cracking down on illegal withdrawals.
- Implementation of modern infrastructure management tools:
- Geographic Information System (GIS)
- Updating potable water network maps
- Establishment of central control rooms (Remote Monitoring & Control)
- Monitoring of hydraulic sector night flow dashboards

4.1 Integrated Governance Reform

Very few wells in Souss-Massa comply with abstraction level and metering requirements (ABHSM, 2021). Remote sensing pilots in Drâa-Tafilalet, in the Atlas region of Morocco, reduced illegal drilling by 40% (ABHT, 2020). Between 430 to 600 ha/year of argan forest lost to urban/agricultural encroachment (HCEFLCD, 2021). GIS-based permits should restrict farming in vulnerable zones (ANDZOA, 2022).

About 95,000 ha are converted to drip irrigation (95% of the target), saving 80 Mm^3 water/year (ORMVASM, 2022). There is need to retrofit 20,000 ha more to reach 100% coverage (Green Climate Fund, 2023), and solar potential: 2,154 kWh/m^2/year in Tata, southeast of Agadir (IRESEN, 2021). Pilot projects: 500 solar pumps installed (25 kW each) are saving 1.2 MWh/year/farm (MASEN, 2022).

Terraced agroforestry reduces soil loss by 60% vs. monocultures (ICARDA, 2020). Target: 10,000 ha of argan/olive intercrops by 2030 (ANDZOA, 2021).

4.2 Technology Integration Solutions

Drought-tolerant wheat (e.g., "Farah") yields 2.5 tons/ha vs. 1.8 tons/ha for traditional varieties (INRA, 2021a). Target has been achieved with 30% increase of cereal area by (DRA-SM, 2022).

Rainwater harvesting potential: 2,000 m³/ha/year captured from greenhouse runoff (Agrotech Solutions, 2021). Twenty-seven small dams built since 2015, adding 12 Mm³ storage (ABHSM, 2022).

4.3 Renewable energy initiatives

The ORMVA of Souss-Massa in collaboration with the river basin agency are initiating Chtouka desalination plant: 400,000 m³/day capacity by 2025 (ONEE, 2022) with the intention to use Hybrid solar wind that could cut energy costs of reverse osmosis desalination systems by 40% (IRESEN, 2022).

Also, the Amskroud wind farm (100 MW) offsets 120,000 tons CO_2/year (ONEE, 2021), with a target of at least 20% of the energy used in the agricultural sector must come from renewable energies by 2030 (MEMEE, 2022).

4.4 Ecosystem-Based Adaptation

Agroforestry expansion targeting 10,000 ha of argan-olive intercrops by 2030 provides erosion control while maintaining agricultural productivity. However, reforestation programs should focus on critical watershed areas to enhance groundwater recharge.

Wetland restoration requires treated wastewater utilization, with potential for 50 Mm³/year application to irrigation of landscaping and ecological conservation (Argan Forest). Green infrastructure development can provide multiple benefits including flood control and habitat conservation.

4.5 Circular Economy Implementation

Current wastewater reuse: 14 Mm³/year out of 55% treated in the basin and the potential of the reuse is 50 Mm³/year by 2050 for irrigation/golf courses (ABHSM-PDAIRE, 2023). The potential agricultural waste usage from crop residues is estimated at 357,768 TOE/year (tons of oil equivalent per year), according to Bartali, and Belmakki (2013). This signifies a significant opportunity to convert agricultural waste into valuable resources, contributing to a more sustainable and circular economy. Also, 5 MW biogas plant operational at COPAG dairy in Taroudant within the Souss Massa basin (SEI, 2021).

CONCLUSIONS

The Souss-Massa River basin demonstrates a critical need for integrated Nexus-based management to address water scarcity, energy sustainability, agricultural competitiveness, and ecosystem conservation and services. The region faces severe water stress with aquifer overexploitation rates reaching 200% and climate projections indicating 20–40% rainfall reduction by 2080. Current sectoral approaches prove inadequate for managing complex interdependencies. Agriculture consumes 93% of water while generating significant revenue from agro-export, necessitating sustainable management to maintain competitiveness. The use of treated wastewater as alternative water and nutrient resources will enhance the circular economy and reinforce the approach of Nexus. Despite achieving high drip irrigation coverage, rebound effects resulted in area expansion, highlighting governance challenges. The study identifies critical gaps including weak enforcement of Law 36-15 (only 5% well compliance), subsidy distortions ($2 billion butane subsidies annually), and fragmented institutional mandates across 12 agencies. The Arganeraie (argan grove) forest loses 600 ha/year while providing essential ecosystem services. Strategic interventions through the Nexus approach include a unified water-agriculture authority, solar-powered desalination scaling, agroforestry expansion targeting 10,000 ha, and circular economy implementation with agricultural waste potential value of 357,768 TOE/year.

The Nexus approach proves essential for balancing economic objectives with ecological limits in water-scarce regions. Success requires integrated policies, stakeholder collaboration, and sustained investment in sustainable technologies. These findings provide an actionable framework for similar arid basins facing comparable resource management challenges globally, demonstrating that integrated management can achieve sustainability while maintaining economic competitiveness. It is also recommended to keep the balance between the nexus components to avoid provoking the integrity of each nexus component.

REFERENCES

ABHDT (Agence du Bassin Hydraulique du Drâa-Tafilalet). 2020. Remote Sensing Pilot Project Impact on Illegal Drilling in Drâa-Tafilalet. ABHT Monitoring Report No. ABHT/RS-2020/015. Brief in ABHT 2020 Workshop Proceedings.

ABHSM-PDAIRE; Agence du Bassin Hydraulique de Souss-Massa, 2023. Etude de révision du plan directeur d'aménagement intégré des ressources en eau (PDAIRE) des bassins du Souss Massa. Données générales des ressources en eau et leur utilisation

ABHSM (Agence du Bassin Hydraulique du Souss-Massa). 2020. Groundwater Depletion and Salinization in Souss-Massa. ABHSM Hydrogeological Report No. ABHSM/GW-2020/012. Agadir: ABHSM.

ABHSM (Agence du Bassin Hydraulique du Souss-Massa). 2019. Etude de Modélisation de L'impact des Changements Climatiques sur les Ressources en Eau au Niveau du Bassin Hydraulique de sous Massa. ABHSM, Agadir, Morcco.

ABHSM (Agence du Bassin Hydraulique du Souss-Massa). 2021. Groundwater Compliance Report. ABHSM: Agadir, Morocco. Technical Report No. ABHSM-2021-GW01, 1-85.

ABHSM (Agence du Bassin Hydraulique du Souss-Massa). 2022. Water Metering Compliance Report. ABHSM: Agadir, Morocco. Technical Report No. ABHSM-2022-WM02, 1-72.

ADA. 2019. Nouvelle Stratégie du Secteur Agricole-Agence Pour le Développement Agricole. Available online: https://www.ada.gov.ma/en/node/79834 (accessed in 2019)

AGRHYMETRegional Center. 2020. Climate Impacts on Crop Cycles in North Africa. AGRHYMET Technical Note No. AGRHYMET/CLIM-2020/005. Niamey: AGRHYMET.

Agrotech Solutions. 2021. Rainwater Harvesting Potential from Greenhouse Runoff. Agrotech White Paper No. ATS/WP-2021/11. DOI:10.13140/RG.00000000.

Aliewi, A., Alomirah, H. 2020. Assessment of the significance of water-energy-food nexus for Kuwait. In: Kumar M et al. (eds) Resilience, response, and risk in water systems, Springer transactions in civil and environmental engineering, pp 357–367. https://doi.org/10.1007/978-981-15-4668-6_19

Albrecht, T.R., Crootof, A. & Scott, C.A. 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters 13(4): 043002.

Al-Zubari, W., ElSadek, A., Mohamed, A. 2018. The water-energy-food nexus in the Arab region, Arabian Gulf University. A policy paper published by the League of Arab States (LAS), with technical and financial support from the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ).

ANDZOA (Agence Nationale pour le Développement des Zones Oasiennes et de l'Arganier). 2022. GIS-Based Permitting for Farming in Vulnerable Zones. ANDZOA Technical Guideline No. ANDZOA/GIS-2022/005.

ANDZOA (Agence Nationale pour le Développement des Zones Oasiennes et de l'Arganier). 2021. Argan/Olive Intercropping Expansion Targets. ANDZOA Strategic Plan 2030, Annex 2. PDF Link (French).

Bartali, E. H. and Belmakki, M. (2013). Morocco country report. Overview of potential biowaste and biobased residues for production of value-added products. M. Gustavsson, Report, Institut Agronomique et Vétérinaire Hassan II, Morocco - Biowaste4SP project.

Brahim, Y.A. 2016. Groundwater depletion assessment in the Souss-Massa aquifer system. Hydrogeology Journal 24(6): 1573-1584.

Choukr-Allah, R., Nghira, A., Hirich, A. & Bouchaou, L. 2017. Water Resources Master Plan for Sustainable Development of the Souss-Massa River Basin. Handbook of Environmental Chemistry 53: 1-26.

CRI-SM (Chambre Régionale d'Agriculture de Souss-Massa). 2020. Compliance Monitoring Report: Groundwater Abstraction and Metering in Souss-Massa. CRI-SM Technical Report No. CRI-SM/WRM-2020/006. Agadir: CRI-SM.

DGPR (Direction Générale de la Protection Civile). 2015. *Post-Disaster Needs Assessment: 2014 Floods in Souss-Massa*. DGPR Disaster Report No. DGPR/PDNA-2015/003. Rabat: DGPR.

DMN (Direction de la Météorologie Nationale). 2019. Climate Trends in Morocco: 1971–2017. DMN Technical Report No. DMN/CLIM-2019/008. Casablanca: DM

DRA-SM (Direction Régionale de l'Agriculture de Souss-Massa). 2022. Cereal Area Expansion Targets in Souss-Massa. DRA-SM Agricultural Policy Document No. DRA-SM/CEREAL-2022/004

DREFLCDSO, 2018. Etude d'aménagement de la forêt de Mesguina. Direction Régionale des Eaux et Forêts et de la Lutte Contre la Désertification du Sud-Ouest. Agadir.

Driouech, F., Riad, S. & Chafiq, B. 2020. Morocco's Climate Trends: CMIP6 Projections. Springer Climate Studies, Berlin.

Ez-zaouy, Y., Lhoussaine Bouchaou, L., Mohammed Hssaisoune, M., Aangri, A., Busico, G., Danni, O.S., Attar, O., Nehmadou, M., Saad, A., Ait Brahim, Y. 2025. Groundwater vulnerability and, risk assessment of seawater intrusion for the development of a strategy plan towards sustainability: Case of the Souss-Massa coastal area, Morocco. Journal of Hydrology: Regional Studies 57 (2025) 102128. https://doi.org/10.1016/j.ejrh.2024.102128

FAO (Food and Agriculture Organization). 2020. Morocco's Agricultural Sector: Climate Vulnerabilities and Adaptation Strategies. FAO Report No. FAO/MOR/2020/002. Rome: FAO.

FAO (Food and Agriculture Organization). 2018. Water Requirements for Moroccan Agriculture Under Climate Change. FAO Land and Water Division Report. Rome: FAO. DOI: 10.4060/CA2521EN

Gommes, R., El Hairech, T., Rosillon, D., Balaghi, R. and Kanamaru, H. 2009. Impact of climate change on agricultural yields in Morocco (World Bank - Morocco study on the impact of climate change on the agricultural sector), Food and Agriculture Organization of the United Nations (FAO). Roma, Italy. 105 p.

http://www.fao.org/nr/climpag/pub/FAO_WorldBank_Study_CC_Morocco_2008.pdf

Green Climate Fund. 2023. Irrigation Retrofitting Requirements for Full Drip Coverage. GCF Project Proposal No. GCF/MAR/2023/01. Project Page.

Günay, C., Haddad, Ch., Gharib, Sh., Jamea El Mostafa., Zejli, D. & Komendantova, N. 2018. Visions of renewable energy futures: co-assessing lessons for Morocco. Linking climate change mitigation, energy security and regional development in climate and energy model regions in Austria. Links-Project Report - FINAL.pdf

HCEFLCD (Haut Commissariat aux Eaux et Forêts et à la Lutte Contre la Désertification). 2021. Argan Forest Loss Due to Urban/Agricultural Encroachment. HCEFLCD Conservation Report No. HCEFLCD/ARGAN-2021/009. Press Release (French).

ICARDA (International Center for Agricultural Research in the Dry Areas). 2020. Soil Loss Reduction through Terraced Agroforestry Systems. ICARDA Research Paper No. 246. DOI:10.1000/xyz123

INRA (Institut National de la Recherche Agronomique). 2021a. Drought-Tolerant Wheat ("Farah") Yield Comparisons. INRA Experimental Report No. INRA/WHEAT-2021/012. Summary (French).

Intergovernmental Panel on Climate Change (IPCC). 2014. AR5 Climate Change Report: Risks and Adaptation in North Africa. IPCC Fifth Assessment Report WGII, Ch. 22: 1199-1255.

International Monetary Fund (IMF). 2021. Morocco Energy Subsidy Review: Fiscal Impacts and Reform Strategies. IMF Working Paper WP/21/189: 1-32.

IRESEN, Institut de Recherche en Énergie Solaire et Énergies Nouvelles.2022. Solar-Wind Hybrid Systems in Morocco: Feasibility and Performance Analysis. IRESEN Technical Report TR-2022-04: 1-89.

IRESEN (Institut de Recherche en Énergie Solaire et Énergies Nouvelles). 2021. Solar Potential Assessment in Tata, Morocco. IRESEN Technical Report No. IRESEN/SOLAR-2021/007. Full Report (PDF).

INRA (Institut National de la Recherche Agronomique). 2021b. Drought-Resistant Crop Trials: Experimental Findings and Recommendations. INRA Monograph Series 15(3): 45-67.

Kingdom of Morocco High Commission for Planning (Haut-Commissariat au Plan, HCP). 2024. *Demographic and Economic Indicators of Souss-Massa Region: Annual Regional Report 2024*. Rabat: HCP. Report Number: HCP/DEMO-REG/2024/003

MAPM. 2017. Agriculture Statistics Report. Ministry of Agriculture and Marine Fisheries, Rabat, Morocco.

MASEN (Moroccan Agency for Sustainable Energy). 2022. Solar Pump Pilot Projects and Energy Savings. MASEN Renewable Energy Report No. MASEN/RE-2022/014. Project Details.

MEMEE (Ministère de l'Énergie, des Mines et de l'Environnement). 2022. Renewable Energy Targets for Moroccan Agriculture. MEMEE Policy Directive No. MEMEE/RE-2030/2022. Official Strategy Document (French).

Ministry of Interior-Morocco. 2015. Regional Monograph of Souss-Massa. Ministry of Interior, Rabat, Morocco.

Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts (MAPM). 2021. Green Morocco Plan (2008-2020): Final Evaluation Report. MAPM Policy Document PD-AGR-2021-12: 1-150.

Moha, M., Redouane, C.-A., Lhoussaine, B., Yassine, A.B., Abdelaziz, H. & Reichert, B. 2017. Evolution of groundwater quality in intensive agricultural zone: Case of Chtouka-Massa Aquifer, Morocco. Arabian Journal of Geosciences 9: 566.

ONEE (Office National de l'Électricité et de l'Eau Potable). 2021. Amskroud Wind Farm Carbon Offset Report. ONEE Sustainability Report 2021, Section 3.2. PDF Link.

ONEE (Office National de l'Électricité et de l'Eau Potable). 2022. Chtouka Desalination Plant Capacity and Plans. ONEE Project Report No. ONEE/DESAL-2022/006. Press Release.

ORMVASM (Office Régional de Mise en Valeur Agricole du Souss-Massa). 2022. Drip Irrigation Conversion and Water Savings. ORMVASM Annual Report 2022, Chapter 4. PDF Link.

ORMVASM (2019). Plan Agricole Régional du Souss-Massa, Agadir, Maroc. http://ormvasm.ma/index.php/fr/2013-11-25-09-37-59/plan-agricole-regional.html

ORMVASM (Office Régional de Mise en Valeur Agricole de Souss-Massa). 2020. *Impact Assessment of Drip Irrigation Modernization in Souss-Massa (2008–2020)*. ORMVASM Agricultural Report No. ORMVASM/IRRIG-2020/009. Agadir: ORMVASM.

Ramos, E.P., Howells, M., Sridharan, V., Engström, R.E. & Taliotis, C. 2020. The climate, land, energy, and water systems (CLEWs) framework: A retrospective of activities and advances to 2019. Environmental Research Letters 15(10): 100201.

Seif-Ennasr, M. 2019. Evapotranspiration and Water Demand Projections for Souss-Massa Under Climate Change. Journal of Arid Environments 163: 1-12. DOI: 10.1016/j.jaridenv.2019.01.002

Seif-Ennasr, M., Zaaboul, R., Hirich, A., Caroletti, G.N., Bouchaou, L., El Morjani, Z.E.A., Beraaouz, E.H., McDonnell, R.A. & Choukr-Allah, R. 2016. Climate Change and Drought Impacts on Water Resources in Morocco: Case Study of Souss-Massa Basin. In: Choukr-Allah R. et al. (eds) The Souss-Massa River Basin, Morocco. Springer Water. Springer, Cham. pp. 307-334. DOI: 10.1007/978-3-319-30630-0_13

Souss-Massa Regional Council. 2017. Regional Renewable Energy Strategy 2017–2022: Solar and Wind Energy Projects. Official Policy Document No. SMRC/RE-2017/005. Agadir: Souss-Massa Regional Council

Stockholm Environment Institute (SEI). 2021. Biogas Potential and Pilot Projects in Morocco's Souss-Massa Region: Case Study of COPAG Dairy Plant in Taroudant. SEI Project Report No. SEI-2021-MOR-004. Stockholm: SEI. DOI:10.51424/SEI.2021.004 (or Full Report PDF).

Stockholm Environment Institute (SEI). 2017. Integrated Resource Nexus Planning for Souss-Massa, Morocco: Waste-to-Energy, Renewable Integration, and Electric Mobility Solutions. SEI Project Report No. SEI-2017-MOR-002. Stockholm: SEI. DOI: 10.51424/SEI.2017.002

Suleiman, M.K., Shahid, S.A. 2023. Prospective of agricultural farming in Kuwait and Energy-Food-Water-Climate nexus. Chapter 15, in Terrestral Environment and Ecosystems of Kuwait (Suleiman, M.K., Shahid S.A. Eds), pp. 363-391, Springer. https://doi.org/10.1007/978-3-031-46262_15

World Bank. 2016. The Economic Costs of Siltation in Maghreb Dams: Case Studies from Morocco, Algeria, and Tunisia. World Bank: Washington, DC. Report No. 103640-MNA, 1-110.

World Bank. 2019. Morocco - Groundwater Governance in the Souss-Massa Basin: Institutional Overlaps and Reform Priorities. World Bank Report No. AUS0001234. Washington, DC: World Bank Group. DOI: 10.1596/1813-9450-1234

World Bank. 2020. Morocco Water Pricing Reform: Economic and Equity Implications. World Bank: Washington, DC. Report No. 145678-MA, 1-92.

Build a New Dam or Improve Irrigation Efficiency? Application of the Water-Energy-Food (WEF) Nexus Framework to Address Resource Scarcity in the Crocodile River Catchment, South Africa

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ABSTRACT

A WEF nexus lens was applied to Mpumalanga Province, where the Crocodile River Catchment is located. It is a crucial agricultural hub in South Africa, producing 25% of the country's staple food on irrigated land. The region faces significant challenges, such as increased water demand and excessive withdrawals, which threaten supply, while water is crucial and interlinked to the energy and food sectors. Three scenarios were analysed to provide decision-making guidance on increasing water availability: A) Building a new dam at the proposed Mountain View site. If constructed, dams should be part of a broader strategy addressing land use to mitigate water storage and quality issues. B) Switching from sugarcane to macadamia. While macadamias offer higher economic value, long-term investments are required, with the switch benefiting the economy through the high export value of nuts. C) Convert from centre pivot to drip irrigation systems. Modernising irrigation infrastructure and enhancing management help achieve efficient water use. Drip irrigation is more efficient than centre pivot irrigation. The conversion of 133 500 hectares to drip irrigation would match the water availability of the proposed dam (78 million m3 yr-1). Energy productivity is estimated to increase from 1.5 kg MJ-1 for sugarcane under pivot irrigation, to 2.0 kg MJ-1 under drip irrigation, and 3.1 kg MJ-1 for macadamias under drip irrigation. Macadamia nuts have higher water footprints and lower irrigation requirements, with a higher export turnover and nutritional value as food than sugar. Transitioning to macadamias and adopting more efficient irrigation systems are the most beneficial actions for the catchment. The long-term returns on water, energy efficiency, and food security justify this approach. The WEF nexus framework provides holistic insights. The WEF nexus approach advocates integrated resource management to promote sectoral synergies and trade-offs that promote sustainable development.

Keywords: Employment, Energy, Food, Footprints, Irrigation, IWRM, Productivity, Water Use Efficiency, Security.

1. INTRODUCTION

Agriculture is the largest consumer of global freshwater resources, and over one-quarter of energy consumption goes to food production and supply (FAO, 2014). Feeding a population of 9.8 billion by 2050 will require 60 percent more food production (FAO, 2014). The primary challenge in agriculture lies in ensuring stakeholders effectively manage resources for optimal benefits (Rehman & Farooq, 2023). This leads to imbalances and duplication of activities, resulting in failure due to resource inefficiencies in South African sectors (Nhamo & Ndlela, 2021). Water-Energy-Food (WEF) nexus thinking recognizes that resources are linked and interdependent. This creates imbalances and lacks sectoral trade-offs (Nhamo et al., 2020). Sectoral imbalances can transfer stress detrimental to other sectors (Drombosky, 2022). The absence of integration increases resource vulnerability through misallocation and degradation (Finely & Seiber, 2014). In the Crocodile (East) catchment, irrigation uses 467 million m³ annually, with commercial forestry using 158 million m³ (DWS, 2021). Water requirements in the Sabie and Crocodile catchments were irrigation (54%), afforestation (22%), urban-industrial (13%), invasive alien plants (6%), and environment (5%). The Inkomati

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TPTC requires 37 million m³ annually to flow into Mozambique (TPTC, 2002). Ecological Water Requirements range from 12.5% to 45.4%. Groundwater extraction is limited except in Kaap and Lower Crocodile rivers areas (DWS, 2021; Mussa et al., 2015). Most catchments lack water resource infrastructure, and climate change will likely worsen water shortages (Dlamini et al., 2023).

In the Mpumalanga region of South Africa's Crocodile River watershed, 25% of staple food is produced on irrigated land, showing the link between food, energy, and water (Simpson et al., 2019). More than 46% of high-potential arable soils are found (BFAP, 2012). In 2013, Mpumalanga's Gross Domestic Product was ZAR 269 863 million, 3.4% of the province's total GDP, with GDP per capita of 64,910 South African Rand, ZAR (OECD Stats, 2018). Mining and agricultural industries' land struggle has affected water quality (Van der Laan et al., 2012). While 65.8% of households had access to improved sanitation in 2015, 91.4% had access to water sources (Walker et al., 2024), and 16.5% reported water pollution (Simpson et al., 2019). Household electricity access increased from 75.9% in 2002 to 89.8% in 2014 (Stats SA, 2015). About 27.4% of households had inadequate food access, giving 74% access to food (Stats SA, 2015). Agriculture uses 70% of freshwater water allocation worldwide (FAO, 2014) and provincially (Taguta et al., 2022). Water stress is high, while energy and food stresses remain low. A balance between water, energy security, and food access is needed. The Department of Rural Development and Agriculture plans to develop 500,000 ha of irrigated land. Building a dam can be explored, while other plans include reducing domestic water demand, replacing irrigation canals with pipelines, removing alien plants, and reducing afforestation.

2. METHODS

WEF nexus concepts and tools were used in a realistic case study by developing decision-making guidance for integrated water resource management (IWRM). A WEF Nexus lens was applied to the issue of water scarcity and increasing demand in the lower Crocodile River Catchment of Mpumalanga. This was linked to the energy and food (agriculture) sectors to show the possible trade-off in these resources. This study aims to compare three plausible scenarios currently being considered by IUCMA to address current and projected water shortages in the Crocodile River Catchment, using a WEF nexus lens to assess the implications for the water, energy, and food sectors, employing quantitative data. Such research information could be used to inform decision-making and future strategic planning, and policy formulation.

2.1 Selection of tools and calculation of WEF Nexus indices

An integrated WEF nexus framework application method was used, where ALF (Analytical Livelihoods Framework: Access, Availability, Lifecycle Assessment: Water Use, Requirements and Energy Productivity and Sustainable Performance Indicators; Cultivated land, Water Stress) using secondary quantitative data were used. To enable comparison across different indicators and components, scores for each indicator are scaled between 0 and 1. The use of spider web plots facilitates the identification of interconnections across various sectors and goals, including trade-offs and synergies (FAO, 2021). Weighting indicators can be further assigned to balance value ranges and represent local priorities, which are subjective and attained through stakeholder consultation (FAO, 2021). Three candidate scenarios were tested:

(a) ‘Scenario A – Develop the resources’: By building a new dam, likely at Mountain View, that could provide an additional yield of 78 million m3 yr-1 [Reconciliation Strategy (DWS, 2018)].

(b) ‘Scenario B: Changing to crops with lower water requirements’: Specifically switch from sugarcane to macadamias (sugarcane uses 15 000 to 17 000 m3 ha-1 yr-1, it is estimated macadamia could use half of this volume of water).

(c) ‘Scenario C: Changing to a more efficient irrigation system’: Specifically switch from centre pivot system to a drip irrigation system and expect an increase in irrigation water use efficiency.

3. RESULTS AND DISCUSSIONS

(A) Building the Mountain View Dam Scenario

Department of Water and Sanitation (DWS) aims to extend the Water Resource Reconciliation Strategy to cover the entire Crocodile (east) and Sabie sub-catchments (portions of supply catchment that were previously neglected). The proposal is to build the Mountain View Dam on the Kaap River (Figure 1 and Figure 2). This dam aims to work with the existing Kwena dam (on the Crocodile River near Lydenburg), to provide releases downstream for irrigators, environmental requirements and international shared water obligations. It will also be used to supply Mbombela, reducing pressure on the Kwena Dam (DWS, 2021). The dam is estimated to cost approximately 873,422,420 ZAR (August 2020 rates). It is reported that no additional infrastructure will be required downstream. The proposed yield of the dam will be 78.1 Mm3 yr-1. It was recommended by DWS (2021) after higher levels of investigation. The dam is estimated to have a maximum height of 74 m and a spillway length of 120 m (DWS, 2021). The following assumptions regarding the dam were made for this study: 1) No hydroelectricity is produced from the proposed Mountain View Dam. 2) Due to the location of the dam, no agricultural land was assumed to be lost because of building the dam. 3) No loss of dam volume due to siltation was considered.

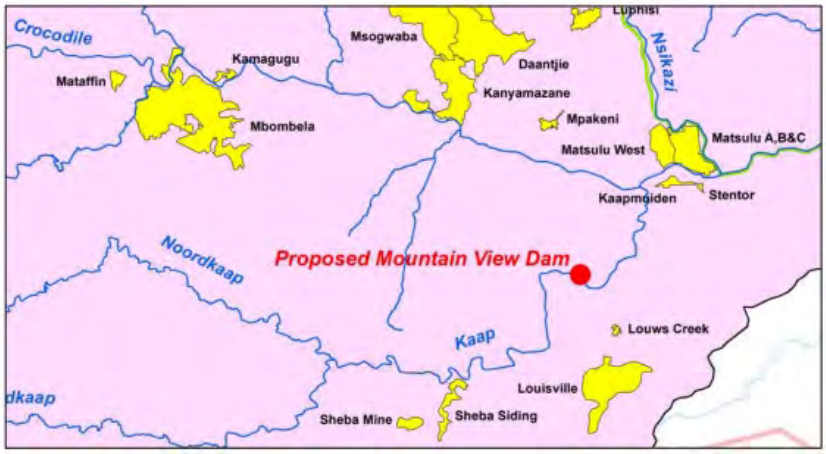

Figure 1. Location of the proposed Mountain View Dam in Mpumalanga (DWS, 2021)

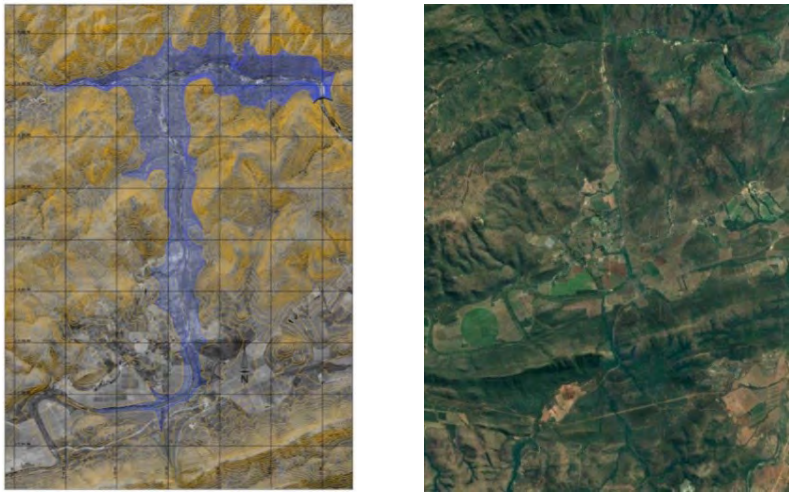

Figure 2. Plan for the proposed Mountain View Dam: (left image from DWS, 2021; right image from Google Earth)

Water sector interventions: An additional 78.1 Mm³ would become available to the region, with primary allocation to Mbombela city. In 2011, the population within Mbombela Local Municipality was 658,604, rising to 695,913 inhabitants in 2016 (Anonymous, 2018a). Assuming a basic human water requirement of 25 litres per person per day (DWA, 2014), the city needs at least 6.4 Mm³ annually for domestic consumption. Jackson (2014) indicated a region-specific volume of 198 m³ per capita per year, equating to 138 Mm³ annually for Mbombela. Jackson (2014) assigned the Crocodile River Water a "C" Classification of moderately polluted, though this data needs updating. When operated with the Kwena dam, this would enhance supply security for users, including irrigation. To utilize this water, high municipal water losses must be addressed, leading to energy savings by reducing water treatment for potable standards. The Kaap River water quality is poor, as it drains an area with active and abandoned gold mines (Van der Laan et al., 2012). If a dam is constructed, it should accompany a careful regional land use and mine closure strategy (Simpson et al., 2019) to avoid future water quality challenges.

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

Food sector interventions: If the current allocation of 54% to irrigation is applied to the new water available from the Mountain View Dam, this could provide an additional 42 Mm3 of water for irrigation. This may enable, for example, the addition of 3780 ha under pivot irrigation, or 11,912 ha of macadamias under drip. Optimistically, this could lead to an increased sucrose production of 55,567-ton sucrose per year or an extra 71,469 ton of macadamia nuts in-shell per year. An overview of all scenarios is provided in Figure 3.

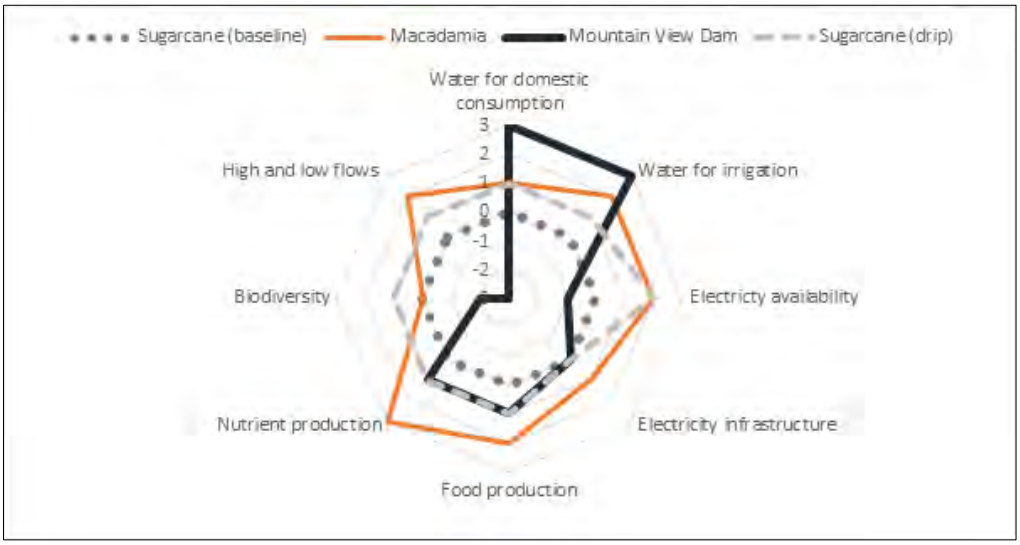

Figure 3. Spider diagram showing the comparison between the three different scenarios using the WEF nexus indices to improve the water resources in the Crocodile River Catchment.

(B) Switching to a more efficient irrigation system and changing to less resource-demanding crops (sugarcane to macadamias) Scenario

Macadamia orchards have become popular in the Lowveld area of Mpumalanga province, replacing forests and other crop plantations. The project evaluated resource use and efficiency in main crops (sugarcane versus macadamia nuts). Since water is limited, macadamias' contribution can be assessed through water and energy costs in production. Sibulali (2021) estimated that 0.53 workers per hectare are needed in the South African macadamia industry. SAMAC (2021) estimated that one full-time equivalent job is created per hectare. Anonymous (2018b) stated that in South Africa in 2017, the macadamia industry created 7750 permanent jobs and 8150 jobs during peak season. In 2020, the industry employed 12,619 permanent and 11,111 seasonal workers on farms (Anonymous, 2018b). The South African sugar industry generated 85,000 direct jobs and

350,000 indirect jobs (SASA, 2024). With 85,000 jobs per 1,862,666 tons of sucrose produced, this equals 0.05 jobs per ton of sucrose, and for 14.7 tons per hectare, approximately 0.67 jobs per hectare. An additional 2.76 jobs per hectare are created indirectly using the same calculation. Macadamia exports in 2017 were R3.3 billion (versus 1.85 million Rand, R for avocados and 320 million R for mangoes) (Genis, 2020). Sibulali (2021) estimated exports grew from 105 million R in 2007 to 4.6 billion R in 2019 supported by Taylor et al. (2021). Over 95% of South Africa's macadamia crop is exported as nut-in-shell or kernels, dependent on international price. According to SAMAC (2021), macadamias have a carbon " C" footprint of 2.3 kg CO2e kg-1 (kilograms of carbon dioxide equivalent per kilogram) nuts produced, while irrigated sugarcane has a "C" footprint of 0.6 kg CO2e kg-1 sucrose (Pryor et al., 2017) (data not shown). The current price of macadamia nuts was 76.50 ZAR (US $5.87)/kg for good quality nuts-in-shell (NIS), assuming 30% "crack-out" and 1.5% kernel moisture content. Sugar export values are currently at $0.49 (8 ZAR) per kg with export volumes having fallen to 389,000 metric tons as of 2022 (Statista, 2024). The current expected average yield was estimated at 4.2 t ha-1 as shown in Figure 4 (Taylor & Gush, 2017).

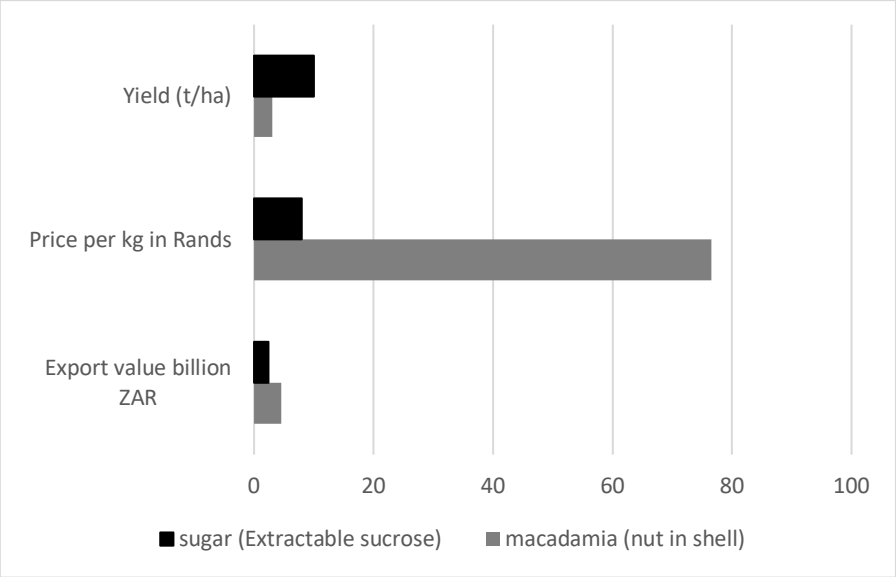

Figure 4. Yield, potential export value and price per kilogram of macadamia (nut in shell) versus sugar (extractable sucrose) (Statista, 2024) produced in the region.

Water sector interventions: Taylor and Gush (2014) reported water use of a macadamia orchard with Beaumont cultivar (M. integrifolia x M. tetraphylla hybrid) in White River, Mpumalanga. For 2011/12, total crop evapotranspiration (ET) was 809 mm (Transpiration, T = 478mm, Soil Evaporation, E = 331 mm), while rainfall received was 887 mm, and irrigation applied was 335 mm. This value was assumed to be the irrigation applied to macadamias in this study. SAMAC (2021) reports 510 litres of water are needed to produce 1 kg macadamia nuts, and it has been reported that 1000 litres of water produces 850 g sugar. Using the assumption that sugarcane requires 1000 mm ha yr-1 while macadamia orchards require 335 mm ha yr-1, achieving water savings to match Mountain View Dam's volume (78.1 Mm3) would require converting 11,744 ha from sugarcane to macadamia production. Sugarcane has high water requirements due to its long formative phase when it remains young and tender, and the hot summer when evaporative demand is high (Kumar et al., 2024). Secondary data and literature were used to compile water use efficiency data to derive results for water productivity (kg/m^3), water footprint (m^3/t), water demands, and irrigation requirements as shown in Table 1. Macadamia (NIS) has lower water input requirement than sugarcane (extractable sucrose). With increased irrigation, water use efficiency decreased (Table 1), however, water productivity increased in sugar cane production (Data not shown). While macadamia trees can be more water-efficient than sugarcane, overall water usage for producing macadamia nuts remains higher than sugar. Mature orchards require 750mm – 850 mm yearly in the Mbombela area (Ibraimo, 2018).

Table 1. Water sectoral comparison of the macadamia (nut in shell) and sugar (extractable sucrose) in terms of water productivity, water footprint, and water requirements.

Factor	Macadamia (NIS) nut in shell)	Sugar (extractable sucrose)
Water Productivity (kg m-3)	0.69a,c	10.4e
Water footprint (m3 t-1)	9000d	210e
Water requirements (mm yr-1)	334c	1000b

a Taylor et al. (2021), b Kumar et al. (2024), c Shabalala et al. (2022), d Ibraimo (2018), e Jarmain et al. (2014)

Energy sector interventions: Converting 11,744 ha of land from sugarcane production under pivot to macadamia under drip, could result in an energy saving of 2.55 GWhyr-1. This only represents 0.1% of the total electricity delivered to Mpumalanga in September 2016 (Stats SA, 2016). Energy productivity is 1.5, 2.0 and 3.1 kg MJ-1 for the sugarcane under pivot, sugarcane under drip, and macadamia under drip scenarios, respectively. A report on CO2 emissions under the different storylines still needs to be compared.

Food sector interventions: Converting 11,744 ha from sugarcane to macadamias would reduce the sugar yield by 172,637 t yr-1 and increase macadamia nut in shell yield by 70,464 t yr-1. High exports and foreign income can counteract a deteriorating currency and support the economy, potentially leading to indirect benefits for food security. The nutritional value of macadamias was also measured in terms of caloric content with a nutritional value higher at 3080kJ/100mg than of sugar cane at 1619kJ/100mg. Macadamia nuts are known to be highly nutritious with multiple health benefits; however, most are not consumed by locals due to concerns about improving food security, particularly in areas affected by malnutrition. Although it is recognised that the nuts are very expensive, their nutritional value is acknowledged. South Africa is self-sufficient in cereal production, but while providing sufficient calories is important, these are often consumed as highly processed, sugar-rich foods, which may still fall short of meeting people's nutritional needs, leading to a condition called "hidden hunger" (Shackleton et al., 2008).

(C) Switching to a more efficient irrigation system (centre pivot to drip irrigation) Scenario

The irrigation water allocations differ within the Crocodile River catchment, with 13 000 m3 ha-1yr-1 allocated to the section above the gorge, and 8 000 m3 ha-1yr-1 to the section below the gorge. Based on Jarmain et al. (2014), it was assumed that sugarcane under pivot irrigation production receives 1000 mm of irrigation water and achieves a sucrose yield of 14.7 t ha-1. The efficiency of drip irrigation of 95% is reported to be higher than for centre pivot at 90% (SASRI, 2017). To achieve a net irrigation of 1000 mm, gross irrigation application of 1111 mm for pivot and 1053 mm for drip irrigation was assumed. Drip irrigation is reported to create more labour opportunities, with 14.4-man days ha-1 yr-1 for drip compared to 1.44-man days ha-1 yr-1 for pivot (SASRI, 2017).

Water sector interventions: Based on the simple assumption that drip is 5% more efficient than pivot irrigation, a total of 133 504 ha would be required to be converted from pivot to drip irrigation to achieve water savings equal in magnitude to the volume of the proposed Mountain View Dam. The 5% higher efficiency of drip over pivot assumed in this study can be considered a conservative number. Further water savings are possible since drip irrigation does not wet the canopy like pivot systems, which results in less water evaporation. utilisation of drip irrigation could also allow for effective irrigation in problem soil areas such as shallow or sandy soils with low water retention, where pivots may not be suitable. In a global data meta-analysis, Taguta et al. (2022) observed that switching from sprinkler to drip irrigation led to an improvement in water productivity of +3.21 kg m-3.

Energy sector interventions: Converting land from sugarcane production under pivot to macadamia production under drip would require 536 kWh ha-1 annum-1, resulting in an energy saving of 2168 kWh ha-1 yr-1. This is similar to the estimate by Oosthuizen et al. (2005) for a drip irrigation system in the Onderberg region of Mpumalanga using 1124 kWh ha-1 yr-1 to apply 718 mm. Due to South Africa's dependence on coal to produce electricity, lower electricity consumption would have long-term impacts on preventing agricultural land from being converted to coal mines, which in turn would have a less detrimental impact on water quality.

Other options need to be looked at as the country and the provinces are currently on an energy crisis due to increased demands that cause stress to the energy sector (Walker et al., 2024) In a global meta-analysis, Taguta et al. (2022) observed that changing from sprinkler to drip improved energy use by +4.4 tonnes MJ-1. Energy productivity is 1.5 kg sucrose MJ-1 for the sugarcane under pivot, compared to 2.0 kg sucrose MJ-1 for sugarcane under drip irrigation. Investment of $ 8 billion USD in irrigated agriculture globally has failed to achieve the intended goals (Ringler, 2017), and many challenges are faced to create sustainable irrigation schemes, especially for small-scale farmers.

Food sector interventions: No change in the production of sucrose was estimated under this scenario, as it compares sugar with sugar. However, drip irrigation is assumed to create more labour opportunities, with 1.44-man days ha-1 yr-1 for pivot and 14.4-man days ha-1 yr-1 for drip. Commercial growers consider 10 to 50 ha the minimum to make a profit, so large tracts of land with access to infrastructure including electricity, water, packhouses and good roads will be required (Genis, 2020). Switching equipment and infrastructure to a more efficient system requires additional system management expertise. While sprinkler systems are cheaper to install initially than pivot or drip systems, more effective systems can justify the investment when water and energy become scarcer. Water for domestic use will become as accessible as irrigation water. Electricity would also be more available for food processing, such as the macadamia and sugar industries. The adoption of renewable or alternative energy sources must be prioritised, along with interventions for the energy sector. Remotely installed solar and wind power systems could help satisfy the energy needs of rural areas. Solar-powered and renewable energy options for irrigation pumps are likely to be crucial for South Africa, as the energy sector faces increasing stress.

4. CONCLUSIONS

Based on benefits in terms of water, energy and food, building a dam as a water resource management strategy, switching some land to a high-value crop and improving irrigation system would be the recommended action for this catchment out of the storylines tested. Positive impacts that could be created by the proposed dam, such as tourism opportunities, should also be more carefully considered in making a holistic decision. The investment to convert areas to macadamia orchards will need to be higher unless it is only in the form of subsidies, but the return on investment would be higher over a longer period. Not all land will be converted to macadamias, but the important motivation will be converting to more water-efficient crops and/or irrigation systems. This WEF analysis lens has been used to demonstrate that by providing information, stakeholders and policy makers can make more informed decisions based on the specific needs of the region. Economics were not the primary focus of this study, but detailed studies are recommended to take the findings of this research further. For accuracy, the study site could be divided into smaller areas for more granular calculations of water savings because of switching to more efficient irrigation systems or crops in different sub-catchments.

REFERENCES

Anonymous. 2018a. City of Mbombela Annual Report 2017/2018. mpg.gov.za/sites/default/files/resources/Annual.Report_2017-2018.pdf Accessed August 2023.

Anonymous. 2018b. The economic value of macadamia farming in SA. https://valleymacs.co.za/2018/12/10/the-economic-value-of-macadamia-farming-i. Accessed 30 April 2024.

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

Department of Water Affairs (DWA). 2014. National Water Resource Strategy. Second Edition. https://www.dws.gov.za/documents/Other/Strategic%20Plan/NWRS2-Final-email-version.pdf.

Accessed 5 May 2023.

DWS. 2018. Long term plans for reconciling water supply and demand for most of the catchments in SA. https://www.dws.gov.za/Documents/Other/WMA/WMA03Crocodile(West)andMaricoWaterManagementArea.pdf. Accessed 11 July 2025

Department of Water and Sanitation (DWS). 2021. Continuation of water requirements and availability reconciliation strategy study for the Mbombela municipal area. Infrastructure and Cost Assessment Report. DWS Report No. P WMA 03/x22/00/6718/6. https://www.dws.gov.za/iwrp/Mbombela/Documents/PDF%20SIGNED%20DOCUMENTS/6%20Infrastructure%20and%20Cost%20Assessment.pdf. Accessed 11 July 2025

Dlamini, N., Senzanje, A. and Mabhaudhi, T. 2023. The water–energy–food (WEF) nexus as a tool to develop climate change adaptation strategies: a case study of the Buffalo River catchment, South Africa. Journal of Water and Climate Change, 14. https://doi.org/10.2166/wcc.2023.263.

Drombosky, I. 2022. Implementing the 2030 Agenda under Resource Scarcity: The Case of WEF Nexus Governance in Azraq/Jordan. In: Governing the Interlinkages between the SDGs. Routledge. ISBN 9781003254683.

Genis, A. 2020. GTAC/CBPEP/EY project on the employment-intensive rural land reform in South Africa: policies, programmes and capacities. Commodity study – Subtropical fruit production by small-scale farmers in South Africa.

https://www.gtac.gov.za/resource/gtac-cbpep-eu-project-on-employment-intensive-rural-land-reform-in-south-africa-policies-programmes-and-capacities-final-report/

Accessed 26 April 2023.

Kumar, N. et al. 2024. Productivity, water use efficiency and soil properties of sugarcane as influenced by trash mulching and irrigation regimes under different planting systems in sandy loam soils. Frontiers in Sustainable Food Systems, 8. https://doi.org/10.3389/fsufs.2024.1340551.

FAO. 2014. The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture. Food and Agriculture Organisation of the United Nations, Rome, Italy.

FAO. 2021. The State of Food Security and Nutrition in the World 2021: Transforming food systems for food security, improved nutrition and affordable healthy diets for all. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Finely, J. and Seiber, J. 2014. The Nexus of Food, Energy, and Water. Journal of Agricultural and Food Chemistry, 62. https://doi.org/10.1021/jf501496r.

Ibraimo, N.A. 2018. Water use of deciduous and evergreen tree nut crops: a case study using pecans and macadamias. PhD Thesis, University of Pretoria, South Africa.

Jackson, B. 2014. An adaptive operational water resources management framework for the Crocodile River Catchment, South Africa. MSc Thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Jarmain, C. et al. 2014. Water use efficiency of selected irrigated crops determined with satellite imagery. WRC Report No. TT 602/14. Water Research Commission, Pretoria. ISBN 978-1-4312-0573-8.

Mussa, F.E.F., Zhou, Y., Maskey, S., Masih, I. and Uhlenbrook, S. 2015. Groundwater as an emergency source for drought mitigation in the Crocodile River catchment, South Africa. Hydrology and Earth System Sciences Discussions, 19(2): 1093–1106. https://doi.org/10.5194/hess-19-1093-2015.

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S. and Modi, A.T. 2020. An integrative analytical model for the water-energy-food nexus: South Africa case study. Environmental Science & Policy, 109: 15–24.

Nhamo, L. and Ndlela, B. 2021. Nexus planning as a pathway towards sustainable environmental and human health post Covid-19. Environmental Research, 192: 110376.

Pryor, S.W., Smithers, J., Lyne, P. and van Antwerpen, R. 2017. Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. Journal of Cleaner Production, 141: 137–145.

OECD STATS. 2018. Organisation for Economic Co-Operation and Development. http://stats.oecd.org/

Accessed January 2022.

Oosthuizen, L.K., Botha, P.W., Grove, B. and Meiring, J.A. 2005. Cost-estimating procedures for drip-, micro- and furrow-irrigation systems. Water SA, 31(3): 403–406.

Rehman, A. and Farooq, M. 2023. Challenges, constraints, and opportunities in sustainable agriculture and environment. In: Farooq, M., Gogoi, N. and Pisante, M. (eds.), Sustainable Agriculture and the Environment. Academic Press, pp. 487–501. ISBN 9780323905008.

Ringler, C. 2017. Investments in irrigation for global food security. International Food Policy Research Institute, Washington DC, United States of America.

SAMAC. 2021. Overview of the South African macadamia industry. https://samac.org.za/industry-overview/.

SASA. 2024. Sugar Industry Statistical Information. https://sasa.org.za/facts-and-figures/

`````````` Accessed 13 February 2025.

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

Shabalala, M., Toucher, M. and Clulow, A. 2022. The Macadamia bloom – What are the hydrological implications? Scientia Horticulturae, 292: 110628. https://doi.org/10.1016/j.scienta.2021.110628.

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

Sibulali, A. 2021. Market Intelligence Report: Macadamia Nuts Industry. Western Cape Government Department of Agriculture. https://www.elsenburg.com/wp-content/uploads/2022/03/2021-Macadamias-MIR.pdf.
``````````

Accessed 26 April 2023.

Simpson, G.B., Badenhorst, J., Jewitt, G.P., Berchner, M. and Davies, E. 2019. Competition for land: The water-energy-food nexus and coal mining in Mpumalanga Province, South Africa. Frontiers in Environmental Science, 7: 86.

Statista. 2024. Total sugar exports worldwide from 2012/2013 to 2024/2025. https://www.statista.com/statistics/495966/sugar-exports-worldwide/

Accessed 30 April 2023.

Stats SA. 2015. General household survey 2014. Statistics South Africa: 174.

Stats SA. 2016. Electricity Generated and Available for Distribution (Preliminary). Statistics South Africa.

Taguta, C., Dirwai, T.L., Senzanje, A., Sikka, A. and Mabhaudhi, T. 2022. Sustainable irrigation technologies: a water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare. Environmental Research Letters, 17(7): 073003.

Taylor, N.J. and Gush, M.B. 2014. The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. Water Research Commission Report.

Taylor, N.J., Smit, T., Smit, A., Midgley, S.J.E., Clulow, A., Annandale, J.G. and Roets, N. 2021. Water Use of Macadamia Orchards (Volume 2). WRC Report No. 2552/2/21. ISBN 978-0-6392-0273-0.

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

Van der Laan, M., Van Antwerpen, R. and Bristow, K.L. 2012. River water quality in the northern sugarcane-producing regions of South Africa and implications for irrigation: A scoping study. Water SA, 38(1): 87–96.

Walker, S., Jacobs-Mata, I., Fakudze, B., Van der Laan, M., Masekwana, S.N., Sawunyama, T. and Machimana, S. 2024. Water-Energy-Food (WEF) Nexus for the Crocodile River Catchment. WRC Report No. 3113/1/23. ISBN 978-0-6392-0576-2.

Implementation of Efficient Agriculture Water Management Practices for Healthy Freshwater Resources and Improved Water-Energy-Food Relationship – A Case Study from Ganga River Basin

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ABSTRACT

Freshwater resources, be it rivers, wetlands or aquifers, while being a crucial source of irrigated agriculture, are equally critical for the well-being of the people and nature. These freshwater resources reel under various pressures related to water quantity and water quality. One of the influencers for pressure related to water quantity is agricultural water use, which is mainly because of an ever-growing gap between the water demand and the water supply owing to a growing population and changing lifestyles. This gap is getting wider due to climate change-related implications.

The food growth systems are dependent on several variables, one of the key inputs is water that is either abstracted or diverted from the rivers or taken out from wetlands/ponds/reservoirs to provide irrigation through canal systems or the water that is pumped out from the aquifers and therefore energy consumption comes into the picture.

In the Ganga River Basin, the state of Uttar Pradesh in India is one of the major stakeholders when it comes to water resources availability, demand and usage. The major water user sector, alone using over 85% to 90% of the available freshwater is agriculture, thus becoming a critical aspect to study when it comes to the management of Ganga's water resources.

A recent study concludes that the water use efficiency in the command area of the Lower Ganga Canal by both sources of irrigation (surface-water and ground-water) is in the range of 33% in Kharif, the season from June to October, to 42% in Rabi, the season from October/November to April/May.

From the perspective of freshwater resources conservation and overall local water security, there is ample scope to enhance the water use efficiency in the agriculture sector, but the apprehensions remain; what if, the water savings are not facilitated for improving the health of river/wetlands/aquifers, but the saved water gets used up to enhance the irrigated area or to widen the cropped area under a more water-intensive cropping pattern.

In the Ganga River Basin, with an aim to conserve freshwater resources and to enhance flows in the local rivulets/streams/tributaries, which also have direct bearing onto the aquifers (as there is strong interconnectedness of surface-water and ground-water, being alluvial plains of the Gangetic plains), an initiative to work with over 300 farmers began in 2017 in Bijnor district of Uttar Pradesh under an irrigation Minor canal, fed by the water resources of Ramganga River – a tributary of Ganga River. The objective was

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to enhance flows in Karula River, part of the Ramganga River System, through the saved water from agriculture water management. This was done by adopting a three-pronged approach of Demand-Side, Supply-Side and Institutional Strengthening.

A proof-of-concept that began with a mere 300 farmers has now been upscaled across 200,000 farmers in over 500 villages of 5 districts of Uttar Pradesh, benefiting 4 tributaries/streams of the Ganga River System. Besides, working towards healthy freshwater resources, the command area farmers have also improved the irrigation water use efficiency in the range of 15% to 20% in case of single crops and about 25% to over 30% in case of intercropping (Kaushal et al., 2022).

This paper narrates the story of an ambitious journey wherein the farmer, the biggest user of freshwater, is not only aiding freshwater conservation for the people and nature but, while doing so, the farmer is also saving energy and contributes to improve the food security scenario in the region. This paper, while presenting a case study from the Ganga River Basin in Uttar Pradesh, India, also demonstrates how efficient agricultural water management practices contribute to water conservation, energy efficiency, and food security, thereby strengthening the Water-Energy-Food (WEF) Nexus.

Keywords: Ganga, WEF Nexus, Irrigation water efficiency, Agriculture water management, Water Users Associations (WUAs).

1. INTRODUCTION

Water is the most critical element of any freshwater ecosystem, be it a river or a wetland or an aquifer. The water, while being the lifeline of any such ecosystem, forms and influences the very character of any water resource. The waters in the surface water systems, like rivers and wetlands, not only support uses of water by the people but also serve a critical and valuable ecosystem service for the biotic (aquatic life, avian and terrestrial biodiversity or fauna) and abiotic (soil, air etc.) components of the ecosystem. Besides this, healthy freshwater systems also shape and influence the micro-climatic conditions in the closer vicinity of such systems.

When it comes to freshwater resources and their use for agriculture, various other critical aspects, like the energy consumption and the food production are often linked as well. However, as noted by Kholod et al. (2021), traditionally, the components of the water-energy-food nexus have been studied and dealt with separately; however, increasingly it has been felt that all three have close inter-relationships and they influence each other. It was concluded that, in an Indian context, much work is required to develop deeper understanding of the inter-relationship between all three elements of the nexus. It is broadly understood that water availability is directly related to food security and water availability itself is influenced by access to energy, as over 70% of irrigation is by groundwater sources. The downscaling of this inter-relationship at a basin-scale or at an irrigation scheme-level is something that will be useful as we develop deeper knowledge in this regard.

On the other hand, Jain et al. (2023), while reviewing the wider inter-relationship of water-energy-food-ecosystem (WEFE) in an Indian context, emphasised the need for integration of the ecosystem into this larger debate around holistically looking at all these critical elements.

Freshwater resources are being utilized for agriculture through formal and informal irrigation systems, managed and regulated by the national or provincial/state or local authorities and, at times, local command area farmers manage such systems. Besides this, there is a large number of farmers that rely on irrigation water supplies from the privately owned tube-wells.

The Ganga River basin is no exception to these irrigation practices, of which a significant river length (1450 km out of over 2500 km) falls in the state of Uttar Pradesh in India (IndiaWRIS). The major freshwater user sector in Uttar Pradesh, alone using over 85% to 90%, is agriculture, thus becoming a critical aspect, when it comes to the sustainable management of Ganga's water resources.

The state of Uttar Pradesh has a wide network of around 75,000 km canals (Sinha 2021), 34,401 State owned tube-wells (Uttar Pradesh Irrigation & Water Resources Department) and numerous shallow tube-wells, that runs into few millions, which are owned by individual farmers. These systems irrigate around 14.38 million ha

area in the state of Uttar Pradesh. Out of which, the canals share is 17%, State Tube-wells share is 3%, Private Tube-wells share is 68% and rest by other sources (Audit Report, Comptroller and Auditor General, 2023). The water use efficiency of both sources of irrigation (surface-water and ground-water) is in the range of 33% in Kharif, the season from June to October, to 42% in Rabi, the season is from October/November to April/May. About 70% of the irrigation in Uttar Pradesh comes from groundwater, pumped through approximately 4 million shallow tube wells—mostly powered by diesel engines operating at merely 5.4% efficiency (WWF India 2010). From the perspective of freshwater resources conservation and overall local water security there is ample scope to enhance the water use efficiency in agriculture sector, but the apprehensions remain; what if, the water savings are not facilitated for improving the health of river/wetlands/aquifers, but the saved water gets used up to enhance the irrigated area or to widen the cropped area under a more water-intensive cropping pattern. Whilst food security is a critical aspect at a national level, healthy freshwater resources are equally vital, as a healthy freshwater resource, be it a river or an aquifer, not only directly aids the farm sector, but also ensures well-being of the people in the vicinity. This is either in the form of groundwater use for irrigation or surface-water for the very same purpose through dams and barrages. Hence, healthy freshwater ecosystems are in the interest of people and nature both.

In the Ganga River basin, with an objective to conserve freshwater resources and to enhance flows in the local rivulets/streams/tributaries, which also have direct bearing onto the aquifers (as there is strong interconnectedness of surface-water and ground-water, being alluvial plains of the Gangetic plains), an initiative to work with over 300 farmers began in 2017 in Bijnor district of Uttar Pradesh under an irrigation Minor fed by the water resources of Ramganga River – a tributary of Ganga River. While the objective of that initiative was to enhance flows in Karula River (part of the Ganga River System) through the saved water from agriculture water management (Kaushal et al., 2022), there is a strong interrelationship of water-energy-food. For instance, the water use at farm level, if reduced or increased will influence the energy use in similar fashion. On the other hand, there will be a bearing onto the agricultural productivity, in view of changed water and input application at farm level. The agricultural productivity, which herein, largely means crops like Maize, Wheat and Sugarcane, are part of larger food security regime in an area.

2. METHODS

2.1 Project area

From the year 2021, having experienced the Karula initiative, which is underway since 2017, the work began with over 200,000 farmers across the irrigation commands in Uttar Pradesh. This work is being done in close partnership with Uttar Pradesh Irrigation & Water Resources Department (UPI&WRD) and concerned District Authorities from Kasganj, Bijnor, Moradabad and Amroha districts of Uttar Pradesh (northern state) in India.

The irrigation systems, which are part of the project area, include –

(a) Lower Ganga Canal System: This perennial irrigation system diverts waters from the Ganga River at Narora Barrage but this irrigation system also gets supplemented by the waters of Ramganga River, through a feeder canal, that brings waters from the Ramganga and extends irrigation service to the command area farmers. While this a much bigger irrigation system, the team is working in the command area of two distributary canals, i.e., the Bachhmai Distributary Canal System and Mohanpur Distributary Canal System, part of Farrukhabad Branch Canal of Lower Ganga Canal. The team is working in this system with over 80,000 farmers. The command area of these two distributary canals falls in Kasganj and Etah districts of the western-central part of the state. This canal system and associated command area is depicted in Figure 1a.

(b) Ramganga Sub-feeder Canal System and Phika-Doab Canal System: These systems divert Ramganga River's water for the purpose of irrigation through a network of irrigation canals in the western part of Uttar Pradesh, including the districts of Bijnor, Moradabad, Amroha and others. The team is working with over 100,000 farmers falling in the command area of these irrigation systems. Apart from this, the team is also working with 100 percent groundwater-dependent farmers (50,000 in number) in non-command-area in these three districts; the idea is to improve the existing farming practices amongst such farmers as well. These canal systems and associated command areas are depicted in Figure 1 b.

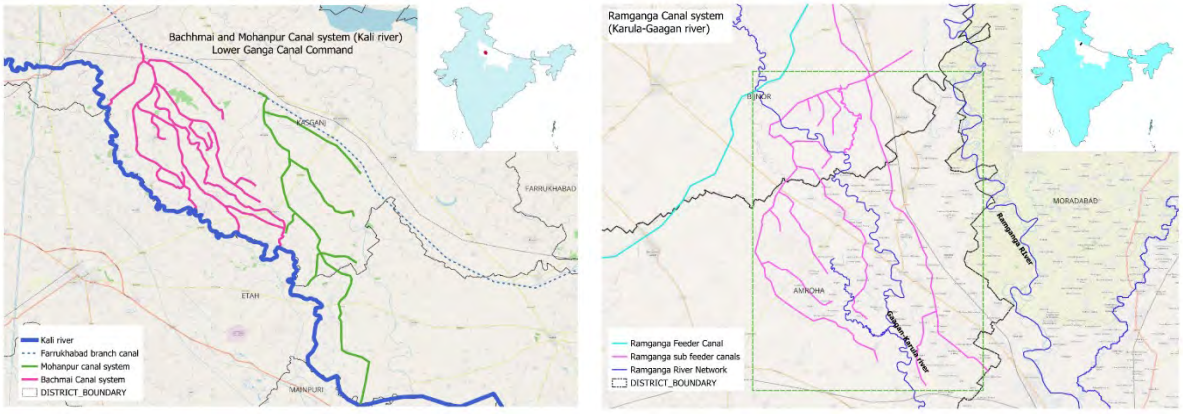

Figure 1 (a) & 1 (b): Map of Bachhmai-Mohanpur canal system (Kasganj district) and Ramganga Canal system (Moradabad-Bijnor-Amroha district) and their proximity with the respective rivers

Both sets of irrigation systems are perennial in nature, i.e. provide irrigation services to the farmers during Rabi and Kharif cropping cycles. While under the Ramganga Sub-Feeder and Phika-Doab canal systems, Sugarcane, wheat and paddy rice are the predominant crops; in the case of the command area of two distributary canals of Lower Ganga Canal, wheat, maize and paddy rice are the main crops.

2.2 Approach and Methodology: Integrated approach to WEF nexus

The approach and methodology for this work is similar to that of the earlier Karula River initiative, i.e. a three-pronged approach, which has a bearing on the elements of WEF nexus. This includes:

(a) Demand-side management: Reducing the irrigation water demand of the farmer and application of sustainable farming ways and means to improve the soil health. Introduction, demonstration and upscaling of efficient irrigation practices was integral to this aspect.

(b) Supply-side management: Upkeep of the irrigation infrastructure to ensure release of designed discharge from the head of the canal system and the swifter and smoother conveyance of water across the canal network up to the farm level. Rehabilitation or construction of a passage from the tail end of the canal to the nearby riverbank or village wetland/pond was a critical element of this aspect.

(c) Institutional strengthening: Awareness, mobilization, capacitating and organizing the command farmers into a Water Users Association (WUA) or strengthening of existing WUAs were the key tasks under this approach.

The work across all three approaches was done simultaneously. However, the usual apprehension remains, i.e., the saved water through these approaches may get used to enhance the area under irrigation or for more water-intensive cropping pattern. To overcome this, the team ran a comprehensive River Health Assessment campaign, through which the farmers were made aware of the importance of their water resources, the rivers, the local wetlands or ponds and the aquifers. The idea was to imbibe the feeling that, they are the biggest user of freshwater, and they can be the biggest saver of this freshwater for the upkeep of these very freshwater resources in their area, which will ultimately help them in overcoming many issues, like – water security, groundwater levels, agricultural produce, input cost, liveable spaces, etc. These farmers are made the 'friends-of-the-river'. In this case, they are named as Friends (Mitras) of Ramganga or Friends (Mitras) of Ganga. In local Hindi language, they are called Ramganga Mitras or Ganga Mitras.

The following flow-chart (Figure 2) illustrates the step-by-step process to execute this work. From Figure 2, one gets an impression of a singular approach around two key aspects, i.e. irrigation water use and economic gains; however, as part of the process, the outcomes are at three levels in the following manner:

(a) Reduced irrigation water requirement leading to lesser water use at farm level, thereby saving water at farm level; both in case of irrigation canal and groundwater. In case, where groundwater is the source of irrigation or the irrigation is supplemented by groundwater, reduced irrigation requirement also means energy savings, as lesser water is pumped out from the aquifer.

(b) Promotion of sustainable and scientific ways and means of agriculture and irrigation leading to reduced input cost, in terms of water application, chemical fertilizers etc. This has a bearing onto the economic proposition of the agriculture.

(c) Enhanced agricultural productivity, in view of optimum and timely water application and practicing agriculture as per the sustainable and scientific ways and means. This, in other words, also means that, the improvement across different crops ensures higher yield of crops like sugarcane, wheat and maize, where the improved practices are demonstrated and implemented.

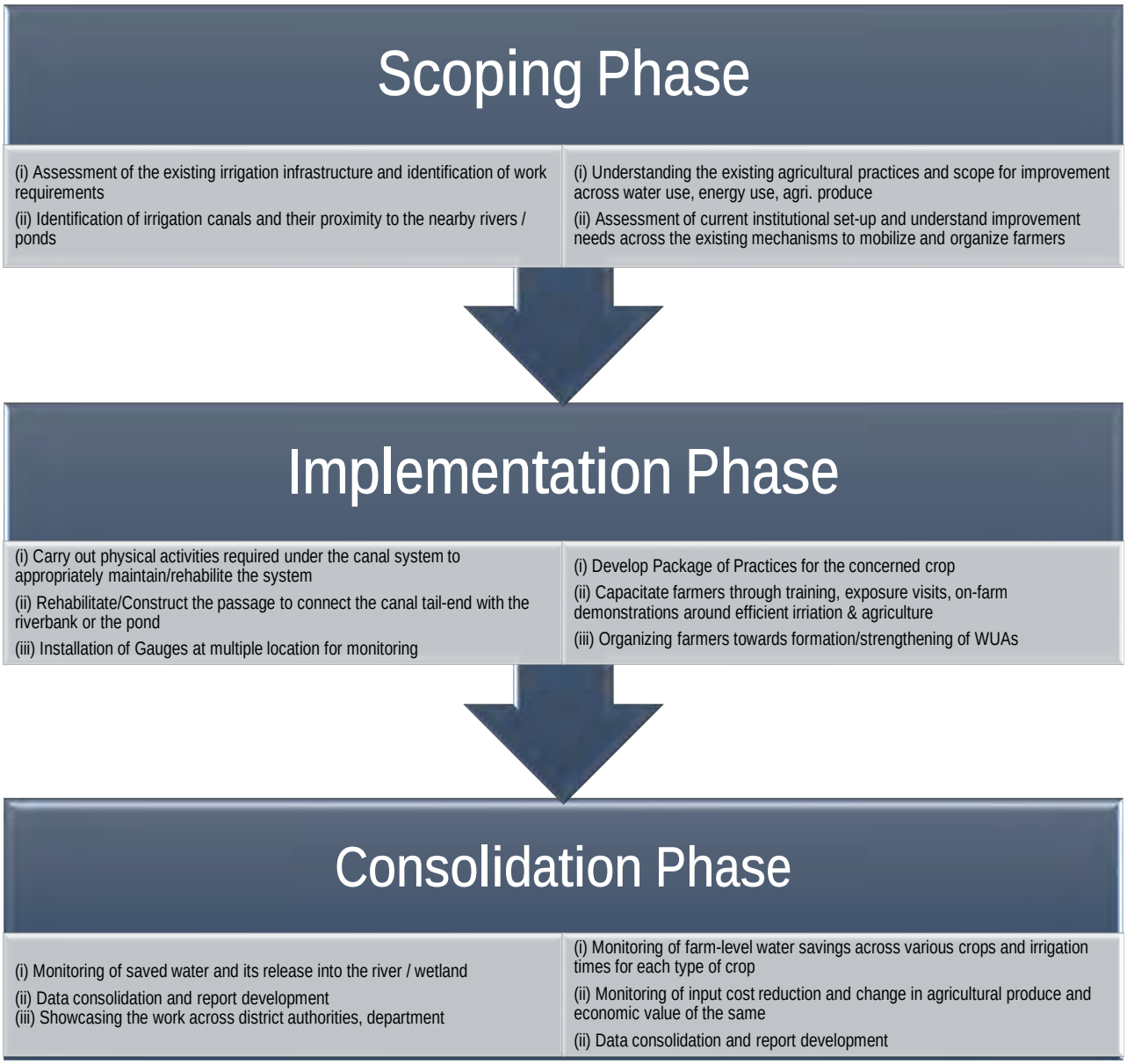

Figure 2: Step-by-step process for implementation of the initiative

2.2.1 Demand Side Management

The demand side management did not take into account following things –

(a) Change in cropping pattern: This is mainly because there is a complete ecosystem to support the existing cropping pattern and a change in cropping pattern will call for many external changes, which were beyond the scope of the project. Plus, a change in cropping pattern is a long-drawn very intricate process, which should be attempted while addressing various forward and backward linkages and complexities. Therefore, the team focussed on the same crops, but looked at some progressive varieties, being promoted by local Agriculture Science Centres (Krishi Vigyaan Kendra) or Agriculture Universities in the vicinity.

(b) Adoption of pressure irrigation techniques: The prevalent irrigation technique is flood irrigation in the region and the farmers would not welcome sudden change to pressure irrigation (like drip and sprinkler), plus such a propagation would call for a substantial assistance by the concerned departments and local authorities. The ongoing experiments in this regard are not able to yield the desired results; hence, the team rather focussed on improvising existing irrigation practices, without involvement of too much of mechanization, so that it is easier for the farmer to adopt.

Nevertheless, it was realized that, if the proposed approach is not economically viable for the farmers, they will not be forthcoming and their wholehearted support would remain a challenge. Therefore, the exposure to and demonstration of improved practices played a key role in convincing the farmers. Because, through demonstrations it was proved that, while trying out the proposed approaches, the farmers will not only save water, but their energy bill will also reduce (in view of reduced pumping) and their farm produce will also fetch enhanced price (in view of improved productivity, in terms of quantity, and quality in some cases).

As part of demand side management, the team, after assessing the 'as-is' scenario through a scoping survey, developed a crop-specific Package of Practice (PoP) document (leaflet in local language with illustrations for easier understanding by the farmer). The farmers were capacitated around these PoPs. As part of demand side management, following measures were taken:

(a) Promotion of line sowing with appropriate spacing. For instance, in case of sugarcane a spacing of 3.5 to 4 feet was proposed, instead of the usual 2 feet. To facilitate line sowing in a scientific manner, the farmers were supported with width adjustable trench tools, which were handed over to the concerned WUAs as an asset to them for use by their command farmers. Line sowing with appropriate width provides several benefits; it helps reduce water application, as the water application is only in rows (unlike flood irrigation, wherein the entire farm is filled with water), improves aeration in soil, provides space and nutrients to crop roots, thereby improving overall health of plant and soil.

(b) Promotion of application of bio-fertilizers and bio-pesticides. Overuse of chemical inputs was not only degrading soil texture, composition, water holding capacity but also impacting good bacteria/microbes which help crops growth. The objective was to improve soil health, reduce chemical usage and increase the use of organic inputs. The farmers were trained to make these organic inputs and they were explained the method of application onto their agricultural farms. This activity has been largely demonstration-oriented.

(c) Promotion of application of micro-nutrients. Depending upon the soil quality, the application of the right micro-nutrients was promoted in the command area.

2.2.2 Supply Side Management

After scoping surveys, as part of supply side management, the following tasks were taken up:

(a) Mapping of tail-ends of the canals with nearby riverbanks or ponds/wetlands, one such case of Bachhmai Distributary Canal system is depicted in Figure 3.

(b) Joint walk-through surveys with the WUAs and department authorities.

(c) Execution of canal rehabilitation and maintenance drive, which in many cases included gates installation at the head of the canals, outlet head pipes, gauge construction and maintenance, etc. Under this activity, those physical works were taken up that are not supported by usual seasonal/annual grant that the department gets from the government.

(d) Rehabilitation or construction of passages from tail-end of the canal to the nearby riverbank or pond/wetland.

2.2.3 Institutional Strengthening

Under institutional strengthening two sets of canal commands are considered, one where WUAs are formed and others are where WUAs are not constituted. In both cases, the team provided required exposure and knowledge exchange opportunities at some of the progressive WUAs across the state and the country. Besides this, the training programmes were conducted for farmers to mobilize and organize them as a vibrant WUA.

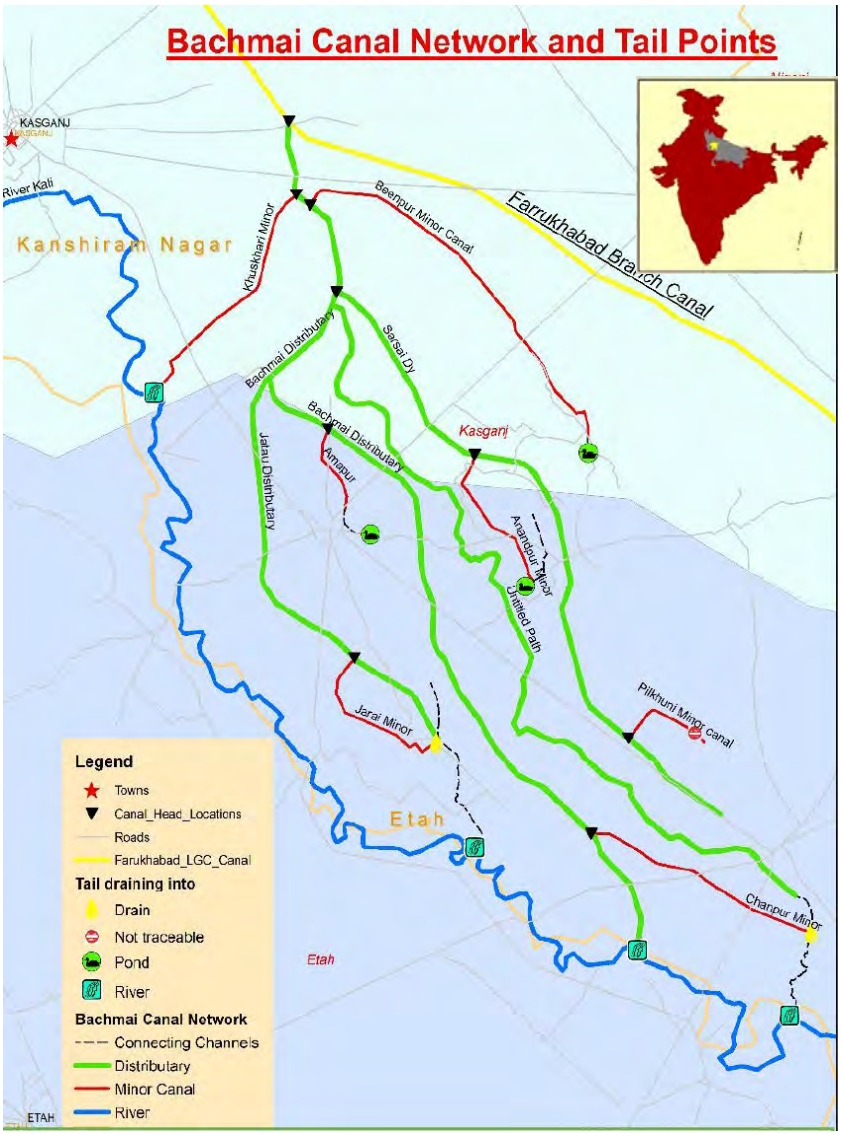

Figure 3: Canal courses and their links with nearby rivers/drains/ponds – an illustration of Bachhmai Distributary Canal system (part of Lower Ganga Canal)

3. RESULTS AND DISCUSSION

This section drives home the message of a healthy water-energy-food relationship, which can lead to effective management of freshwater resources. This is mainly because the benefits accrued from this initiative have not only led to water efficiency gains, but have also led to improved agricultural produce, both in terms of quantity and quality. As the demand side interventions lead to reduced water application at farm level, hence, even the 100% groundwater dependent farmers also gained, as they had to use much less energy to draw the groundwater for their farms.

Whilst the analysis of the data of such a large number of farmers would be an enormous task, the team worked on a sample size of about 10% of the total number of engaged farmers. This sample size ensured adequate representation of various typologies, like :

- Farm-size
- Canal reach, i.e. head-middle-tail
- Crop type, i.e. sugarcane, maize and wheat
- Geographical representation
- Irrigation source-wise (canal, groundwater and conjunctive)

The results given in Table 1 are derived from the analysis of the findings from this sample size.

Table 1: The gains in terms of water use efficiency, energy efficiency, agricultural productivity for Sugarcane, Wheat and Maize

		Traditional approach (per hectare)			Improved approach (per hectare)			% increase in water use efficiency	% decrease in Avg. Energy Use	% increase in avg. Production
No	Crop Type	Avg. Water Use (Million Liters)	Avg. Energy Use (kWh)	Avg. Production (Tons)	Avg. Water Use (Million Liters)	Avg. Energy Use (kWh)	Avg. Production (Tons)			
1	Sugarcane	15.4	571	68.8	12.3	328	89.4	20	43	30
2	Wheat	4.4	267	4.1	3.71	180	5.2	16	32	25
3	Maize	3.58	486	7.6	3.09	320	10.3	14	34	35
Note: As farmers practice conjunctive use of water in project area the calculations are based on a field-based assumption that 60% of irrigation for a crop is by groundwater and 40% by canal water. This is generally a feature in the project area. Herein, the data of non-command area farmers are not included.										

The data in Table 1 are discussed in a detailed manner in the upcoming sub-sections.

3.1 Irrigation Water Use Efficiency

Similar to earlier published work (Kaushal et al., 2022), the water use efficiency at farm level has been as follows:

(a) **Sugarcane:** 15-20% efficiency gains (average 20%); intercropping (e.g., mustard) achieved 25-30%.

(b) **Maize:** 15-20% gains (average 14%); improved trencher sowing aiding optimum row-to-row spacing, soil management, and optimal irrigation scheduling.

(c) **Wheat:** 15-25% gains (average 16%) through adjusted irrigation frequency, variety selection, and balanced fertilizer application.

3.2 Change in agricultural produce

The interventions led to increased agricultural yields and improved produce quality. The adoption of bio-fertilizers and optimized nutrient management reduced input costs, enhancing farmers' profitability.

Agricultural productivity, particularly for sugarcane, has seen a notable rise — increasing from 68.4 tons per hectare under traditional practices to 89.4 tons per hectare with the adoption of package of practices (PoPs), marking an improvement of close to 30% (29.36%).

Farmers' average income also increased substantially by Indian National Rupee10 ₹36,812 (US $ 431), moving from ₹1,20,013 (US$ 1,404) to ₹1,52,345 (US$ 1,783) per hectare, representing a 30.68% growth. Simultaneously, input costs—including irrigation, fertilizers, and pesticides—have decreased from ₹50,699 (US$ 593) to ₹40,947 (US$ 479) per hectare, amounting to a reduction of ₹9,752 (US$ 114) or 19.24%.

3.3 Flow releases into different rivers and ponds from tail-ends of various canals

From 2021 until the present date, over 5.4 billion litres of saved and available water from about 20 irrigation canals is released into 4 rivers, namely – Karula, Gaagan, Ramganga, Kali and local village ponds. Flow releases in a river and pond-wise manner are depicted in Table 2.

Table 2: Volume of saved and available water release into rivers or ponds

No.	Irrigation System Name	Water released in Million Litres
1	Bachhmai & Mohanpur Irrigation (Lower Ganga Canal)	2052
2	Ramganga Sub-Feeder Irrigation Canal System and other associated canal irrigation systems	3404
	Total volume released (Million Litres)	5456

Now, as and when the canals are in running condition, the water after serving the irrigation needs joins the river or the pond to enhance the water in these freshwater ecosystems or improves local water security.

3.4 Energy Efficiency Gains (Energy Security)

Reduced water application directly lowered the energy required for groundwater pumping, benefiting even the fully groundwater-dependent farmers. Lower energy consumption translated into cost savings and reduced environmental impacts.

Enhancing the water holding capacity in soil through use of organic input helps in reduction of water consumption at farm level. It also reduces the time required per watering (of the farm). The energy savings are maximum in case of Sugarcane crop, which is in the range of 43%; whereas in case of other two crops, this value is in the range of 32% to 34%.

In view of the application of efficient irrigation practices, the farmers observe reduced time being taken up for irrigating the farm; this has also reduced electricity consumption and therefore the cost incurred by them. The reduced usage of ground water (by 15-20%) while changing the irrigation and agricultural practices, like – trencher-based line-sowing with optimum row-to-row spacing and more organic carbon (through use of organic inputs like bio-pesticides and bio-fertilizers (Amrit Pani – "Nectar Water" or "Immortal Water" and Jeeva Amrit, a natural, liquid organic fertilizer), enhances efficiency across water and energy use.

3.5 Socio-institutional outcomes

The formation and strengthening of WUAs fostered community-based water management, promoting knowledge exchange and collective action. Farmers' involvement in monitoring and maintaining water resources enhanced their stewardship and local water security.

10 US Dollar $ = Indian National Rupee ₹ 85.45 (exchange rate as on June 28, 2025).

CONCLUSIONS

This case study demonstrates the interconnectedness of water-energy-food in an Indian context, emphasizing the need for integrated approaches at basin and irrigation scheme levels. While water availability directly influences food security and is itself dependent on energy for irrigation, this initiative highlights the multidimensional benefits of efficient water management. The conjunctive use of surface-water and ground-water is a reality in canal command areas, and hence the irrigation water use efficiency across the canal commands has direct bearing onto the energy use. Hence, though on first view, it may appear to be a specific initiative, mere around water use efficiency, it actually has influence on energy consumption as well (as noted in Section 3.4), as reduced irrigation demand curbs energy consumption. On the other hand, the food or agricultural production is an apparent link here; wherein, due to improved irrigation and agricultural practices, there is enhanced and improved agricultural produce, which translate into monetary gains as well (as reported in the Section 3.2).

Building on the work presented, it can be concluded that there is a clear need for integrated, holistic programs that recognize and leverage the interconnections of the WEF Nexus. Such approaches offer scalable solutions for sustainable development, particularly in water-stressed and agriculturally intensive regions like the Ganga River Basin.

There is also an additional dimension to this dialogue of water-energy-food, which is the ecosystem health. The agriculture water management work presented in this paper exemplifies the multidimensional benefits that may be accrued while working on such an initiative. While the larger goal has been to enhance flows in the streams/rivulets to achieve the Environmental Flow regime in the rivers, as part of the process, not only the farmers, but the freshwater resources also benefited. It fits well in a water-energy-food-ecosystem (WEFE)-centric thought process, as advocated by many researchers. Echoing the findings of Jain et al. (2023), the authors recognize that public and welfare schemes are required to be designed keeping in mind the very interconnectedness of WEFE; there is a need to develop specific analytical frameworks and methods in a systems approach for informed policy development.

Going forward, there is a need to develop integrated and holistic programs and projects that can showcase multidimensional benefits or, at least, bearings across the aspects of WEFE. And, for such an endeavor, the work presented in this paper gives key pointers on the design and execution of such ambitious journeys. The much talked about water-energy-food-ecosystem relationship is set to draw benefits as well; because water is central here and the work around better management of water will have direct bearing onto all the aspects of WEFE.

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REFERENCES

Comptroller and Auditor General (CAG) Audit Report Chapter 1 (2023). Government of India. https://cag.gov.in/uploads/download_audit_report/2023/5-Chapter-I-064d38586a8b190.10582449.pdf (accessed on 04/07/2025)

IndiaWRIS. Water Resources Information System. Government of India.

https://indiawris.gov.in/wiki/doku.php?id=uttar_pradesh (accessed on 04/07/2025)

Jain, S.K.; Sikka, A.K.; Alam, M.F. (2023) Water-energy-food-ecosystem nexus in India—A review of relevant studies, policies, and programmes. Front. Water 5, 1128198. doi: 10.3389/frwa.2023.1128198.

https://www.frontiersin.org/journals/water/articles/10.3389/frwa.2023.1128198/full

Kaushal, N.; Babu, S.; Mishra, A.; Bajpai, R.; Sinha, P.K.; Arya, R.K.; Tickner, D.; Linstead, C. Securing Flows in the River Systems through Irrigation Water Use Efficiency—A Case Study from Karula River in the Ganga River System. (2022). Water, 14(18), 2894. https://doi.org/10.3390/w14182894

Kholod, N.; Evans, M.; Khan, Z.; Chaturvedi, V. (2012). Water-energy-food nexus in India: A critical review. (2021). Energy and Climate Change, 2, 100060, ISSN 2666-2787, https://doi.org/10.1016/j.egycc.2021.100060

Sinha R.S., State of Groundwater in Uttar Pradesh: A Situation Analysis with Critical Overview and Sustainable Solutions (2021). Wateraid India. https://cdn.cseindia.org/gic/state-of-ground-water-20210927.pdf (accessed on 04/07/2025)

Uttar Pradesh Irrigation & Water Resources Department. State Tube-wells. https://www.idup.gov.in/en/page/tube-well (accessed on 04/07/2025)

WWF India study on Problems and prospects of saving water and energy in agriculture in Upper Ganga River Basin (2010). http://awsassets.wwfindia.org/ (accessed 02/07/2025)

Perceptions and Implementation of Climate Adapation Programs: Leveraging Adaptive Capacity of Rice Farmers in Takeo Province, Cambodia

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ABSTRACT

Agricultural production in Takeo province, south Cambodia, largely depends on irrigation canals from which farmers use diesel irrigation pumps. Rising climate variability intensifies pressure on water resources, and irrigation energy demand. In response, climate-smart tools such as the Climate-Smart Maps (CS Maps) have been developed to identify localized climate risks and recommend zone-specific adaptations. CS Maps, developed by the International Rice Research Institute, were later adapted for Cambodia in collaboration with the Ministry of Agriculture, Forestry and Fisheries. Suggested adaptations include adjusting cropping calendars, diversifying crops, integrating animal husbandry and aquaculture, upgrading irrigation infrastructure, and developing additional sources of irrigation water. This study explores two core issues: (1) farmers' perceptions of climate adaptation need, (2) their capacity to adopt CS Map recommendations and (3) assess the need for WEF-Nexus implementation. A questionnaire survey (n = 230) across 23 communes in Takeo province conducted in December 2024 revealed that 83–94% of farmers observed decreased rainfall and increased extreme heat events. Despite this, only 35% support crop calendar adjustments, while 47% and 77% prefer a shift to high value agriculture through crop diversification and animal husbandry, respectively. Knowledge (only 32–42% feel sufficiently informed) and finances remain key barriers for climate adaptations. Contrary to common perceptions, 63–73% of respondents are willing to invest financial and labour resources for irrigation improvements while demanding for necessary knowledge. Most farmers experience substantial climate risk, while they do not feel adequately informed about implementing climate solutions. Given the variation in resource mobilization preferences across adaptation options, effective knowledge sharing is essential. Overall, the study highlights insufficient credit and knowledge as key issues holding back the implementation. The majority of farmers (76%) use pumps, farmers view energy as routine for secured water supply, not a constraint for adaptations. Energy remains unaddressed as a controllable factor in adaptation. Climate-smart strategies must consider efficient and productive water use along with a climate-smart energy network to create low-emission, resilient, and productive agricultural systems.

Keywords: Climate Adaptation, Climate-Smart Maps, CS Maps, Water–Energy–Food Nexus, Sustainable Agriculture, Capacity Building.

1. Introduction

The widespread consequences of anthropogenic climate change are clearly evident across the globe. Global warming is predicted to increase by 1.4°C to 4.4°C between 2081 and 2100, with the consequences becoming more severe (IPCC, 2023b). The climate crisis is often perceived as a water crisis, as it leads to a range of water-related challenges, including floods, droughts, extreme rainfall events, shifts in precipitation patterns, water shortages, and deteriorating water quality, alongside temperature extremes. The IPCC (2023a) emphasizes, with high confidence, the risk posed by climate-induced alterations in the water cycle, including increased variability, changes in global monsoon patterns, and the frequency of extreme wet and dry events in the near future, agriculture is one of the most vulnerable sectors to climate risk. Significant crop yield reductions and variabilities are observed across the globe (Kukal & Irmak, 2018; Lesk et al., 2022; Rezaei et al., 2023). In addition to the escalating water crisis, energy demand is also rising, driven by increased

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competition for limited water resources and reduced water availability. On the other hand, water scarcity can constrain energy generation and disrupt key processes that depend on reliable water supplies, adding further strain to already stressed systems. This growing interdependence highlights the urgent need for integrated water-energy-food management under climate stress. The Water-Energy-Food (WEF) Nexus is a conceptual framework that emphasizes the interdependencies and interconnectedness of water, energy, and food systems in order to achieve sustainable development and reduce trade-offs, build synergies and improve governance across sectors. It recognizes that actions in one area often have impacts on the others and aims to promote integrated management for sustainable development (FAO, 2014).

These global challenges manifest acutely in regions like Southeast Asia, where densely populated and agriculture-dependent areas are highly exposed to climate variability. The Mekong Delta in Southeast Asia is a critical component in global food security, providing sustenance to 300 million people annually. However, the Mekong Basin is increasingly pressured by climate change, resulting in reduced water availability for crops and posing a significant threat to food security (Schneider & Asch, 2020). Along with Vietnam, Cambodia has been recognized a Southeast Asian country with the highest risk of rice agriculture (Taniushkina et al., 2024). Cambodia is projected to experience climate risks, including a temperature increase of 1.24°C between 2040 and 2059. The country is also expected to face drier dry seasons and wetter wet seasons, with heightened spatial-temporal variability and more frequent and intense rainfall events by mid-century (WBG, 2024). These projections highlight substantial risks to Cambodia's agri-food systems, with water resources expected to face increasing stress due to climate variability. This growing pressure on water availability is likely to undermine agricultural productivity, ultimately posing serious challenges to national food security. Despite the growing role of energy in irrigation and agriculture sector, empirical data on energy demand dynamics in Cambodia remain scarce. This data gap presents a critical barrier to effective planning and underscores the need for evidence-based strategies tailored to the WEF nexus under climate change.

To safeguard food security while lowering water and energy demand amid escalating climate risks, it is vital to adopt agricultural adaptation strategies that reduce vulnerability and support sustained WEF nexus. The adaptations may include cropping calendar adjustments, adoption of climate-resilient crop varieties, improved water management, soil conservation practices, and diversified farming systems. These adaptation approaches have long been recognized, and key implementation barriers have been identified at the national scale (D'Agostino & Sovacool, 2011). Considering the diverse agro-hydrology across Cambodia, a climate adaptation strategy tailored to local contexts is likely to be more effective and appropriate from the perspective of practitioners. The International Rice Research Institute has recently developed Climate-Smart Maps (CS-Maps) to identify location-specific climate risks and recommend corresponding adaptation strategies for each climate risk class, using a participatory approach.

However, one of the key challenges lies in identifying context-specific strategies that align with local conditions and in assessing the adaptive capacities of farming communities to implement these measures effectively. The ability of agricultural communities to adjust to, cope with, and recover from climate impacts plays a critical role in the success of any climate adaptation plan, which is defined as adaptive capacity. The adaptive capacity depends on multiple factors such as natural, agro environmental, governance, scaling innovations, socio economic factors access to climate information, and financial resources. Effective implementation of a climate adaptation plan requires a thorough understanding of existing adaptive capacities and the gaps that hinder resilience, in order to inform targeted capacity-building efforts. Therefore, this study aims to identify (1) farmers' perceptions of climate adaptation needs, (2) their capacity to adopt CS Map recommendations and (3) assess the need for WEF-Nexus implementation.

2. Methods

2.1 Study area

The research was carried out in Takeo Province, south Cambodia, an area characterized by an annual rainfall of 1,690 mm. A considerable part of the province faces annual floods around September – November period mainly from the Bassac River, a tributary of the Mekong River.

In general, Takeo Province experiences a wet season from June to October and a dry season from December to March. However, within these seasonal boundaries, there is considerable variation in the timing and availability of cropping windows across individual paddy fields. This variability is primarily influenced by factors such as water availability, field elevation, and flood occurrence. During the wet season, three distinct cropping windows can typically be observed: (1) early wet season, which is cultivated with short- to medium-duration rice varieties; (2) long wet season, with long-duration rice varieties; and (3) late wet season, which again favours short- to medium-duration rice varieties.

The agriculture in Takeo province is dominated by rice cultivation under both irrigation and rain fed systems. Irrigated systems may include canal networks linked to rivers, reservoirs that collect rainwater and distribute it via canals, or systems that rely on groundwater pumping. Takeo Province exhibits extensive use of water pumping for irrigation, with a significant reliance on canal sources. Canal water levels exhibit significant temporal variability, with periods of low water height requiring the use of pumping to ensure adequate irrigation supply.

2.2 Climate smart maps in Takeo

The Climate-Smart Maps (CS-Maps) were developed by the International Rice Research Institute (IRRI) using a participatory mapping approach in three target countries. The Ministry of Agriculture, Forestry and Fisheries, Cambodia collaborated with IRRI in developing CS-Maps in four provinces in Cambodia including Takeo. Figure 1 presents the CS-Map for Takeo province under the potential drought risk for rice in normal years. These maps serve as a decision-support tool to delineate climate risk zones within selected provinces and propose tailored zone-specific adaptation strategies to inform climate-resilient agricultural planning. In a normal year, areas with the highest climate risk for rice cultivation are indicated in red, while those with the lowest risk are marked in green. Each color-coded zone corresponds to a distinct climate risk class, with a total of 23 identified classes, each associated with a specific adaptation strategy. Suggested adaptations include adjusting cropping calendars, diversifying crops, integrating animal husbandry and aquaculture, upgrading irrigation infrastructure, and developing additional sources of irrigation water. (IRRI, 2024).

2.3 Data collection

A structured questionnaire survey was conducted to assess farmers' perceptions of climate change, as well as their capacity and willingness to adopt the adaptation measures recommended by the CS-Maps. One commune was randomly selected from each climate risk class in Takeo province, and ten rice farmers were randomly selected within each commune, resulting in a total sample size of 230. The survey was carried out over the first 2 weeks of December 2024, an e-survey using KoboToolbox and KoboCollect App (www.kobotoolbox.org).

3. Results and discussion

3.1 Demographics of the sample

The sample comprised rice farmers, the majority of whom identify farming as their primary occupation, accounting for 91% of respondents. The average age of participants was 51 years, with ages ranging from 25 to 75 years. Female respondents represented 34% of the sample. In terms of educational attainment, 10% of the respondents were illiterate, while 43% had received at least a secondary-level education. On average, the respondents had 29 years of farming experience, with individual experience ranging from 2 to 55 years. Approximately 35% reported the presence of farmer associations in their area, yet only 25% indicated that they were members of such associations.

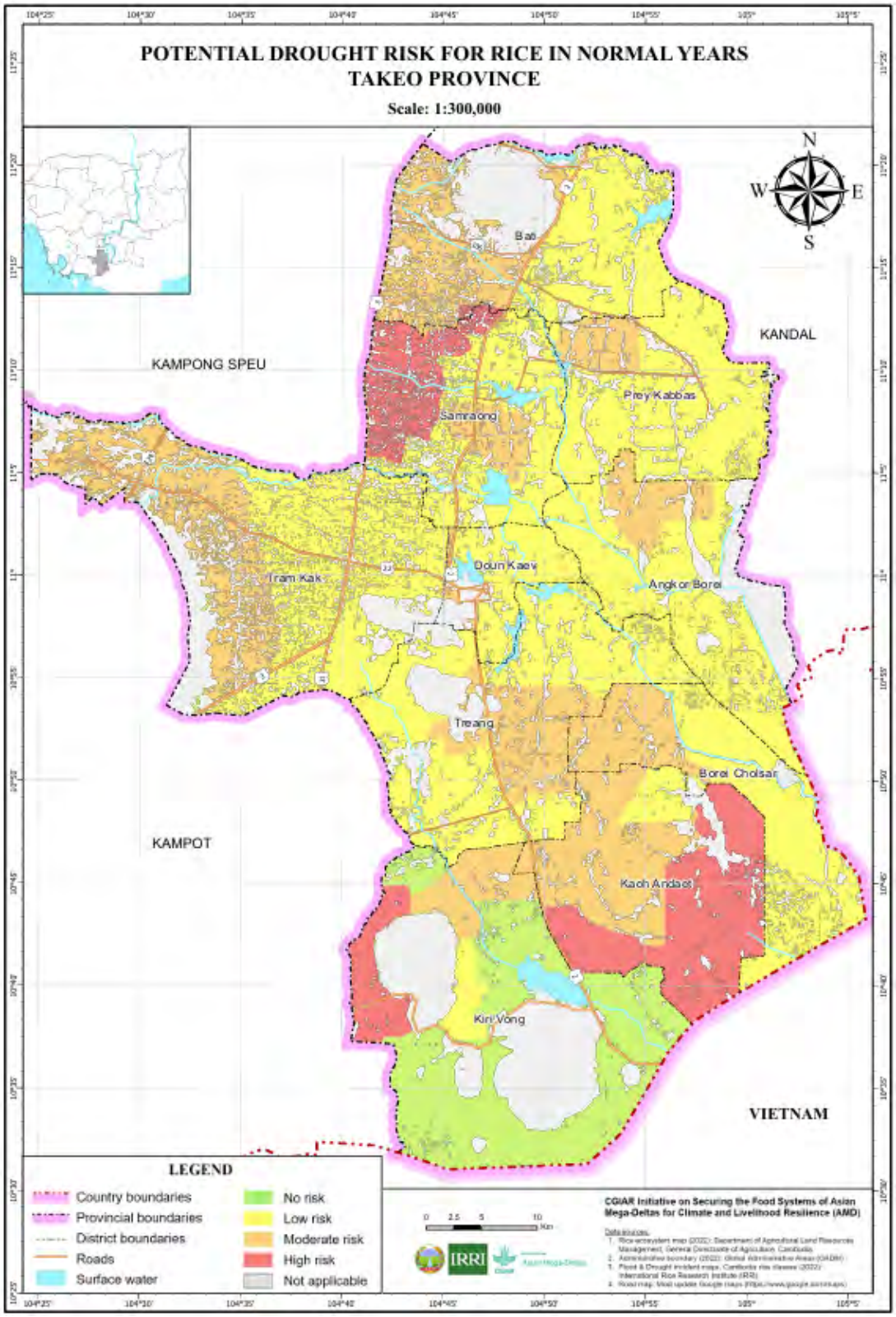


Figure 1: Climate-Smart Map showing climate risk classes in Takeo province Source: (IRRI, 2024)

3.2 Farmer observations and perceptions on climate-water risk

Farmers across Takeo have observed changes in weather patterns over the last two decades that affect their agricultural activities, such as irregular rainfall, temperature extremes, and shifting rainfall seasons (Table 1).

Table 1: Climate observation of the farmers in Takeo, referring to the last 20 years

Climate observation referring to the last 20 years	Percent respondents (%)			
	Yes	No	No idea	Not Relevant
Rainfall has become more irregular	91.74	7.83	0.43	0.00
The amount of rainfall has increased	18.26	76.96	4.78	0.00
The amount of rainfall has decreased	83.04	12.17	4.78	0.00
The duration of rainfall has increased	18.70	78.70	2.61	0.00
The duration of rainfall has decreased	86.96	9.13	3.91	0.00
Rainfall starts later and ends earlier	93.91	4.35	1.74	0.00
Rainfall distribution over the season is poor (with more peaks)	94.35	2.61	3.04	0.00
Temperature extremes are more common now	85.22	10.87	3.91	0.00
Long dry spells (longer than usual) occur during the dry season	75.22	10.87	13.91	0.00
Flood heights have increased	18.26	35.65	17.83	28.26
Flood heights have decreased	35.65	18.70	17.83	27.83
Areas that were never flooded are now experiencing floods	26.52	24.35	19.57	29.57
Areas that used to be flooded are no longer experiencing floods	29.13	20.43	21.74	28.70

A majority of respondents indicated that rainfall patterns have become increasingly irregular (92%), with notable shifts in the timing of rainfall events (94%) and comparatively uneven distribution throughout the season, often characterized by more frequent peak intensities (75%). In fact, 83% of respondents reported a decrease in the amount of rainfall, while 87% observed a reduction in the duration of rainfall. Many farmers experienced more prolonged dry spells than usual (85%) and also an increased frequency of temperature extremes (94%). Variations in flood height responses were inconsistent, suggesting that changes may be influenced by localized micro-elevation differences. These changes may have an effect on planting schedules, crop yields, and water availability. Such firsthand observations highlight the growing challenges climate variability poses to traditional farming practices and rural livelihoods.

Overall, farmer perceptions of water availability are generally positive, however, there is notable variation that warrants further investigation (Table 2). Among the respondents, 63% reported having sufficient water to irrigate rice crops in any season, while a higher proportion (74%) believed they had adequate water during at least one season. However, approximately 50% of farmers reported relying on multiple water sources for irrigation. This reliance suggests that the primary water source is perceived as unreliable, prompting the use of alternative sources as an adaptation strategy in response to climate-related uncertainties. Such dependence on multiple sources may lead to increased operational costs, particularly in terms of labour, time, and especially energy consumption. In Takeo, water pumping is not limited to groundwater extraction; pumping from surface water sources is also a common practice. Due to significant seasonal fluctuations in canal water levels, pumping is often required to ensure adequate water supply to agricultural fields situated at elevations higher than the canal, mostly in dry or early wet seasons. Very high proportion of the sample (76%) use irrigation water pumping at least once during a cropping year emphasizing high energy use for the pumping.

Climate risk is further highlighted by the finding that half of the respondents reported at least one family member leaving agriculture due to climate-related challenges. Despite these individual adaptive measures, collective or community-level actions for water management and climate adaptation remain limited and underdeveloped.

Table 2: Farmer perceptions on water availability

Water availability statements	Percent respondents (%)		
	Yes	No	Not Relevant
Water is available as much as the rice crop needs in any season, throughout the last 5 years	62.6	37.4	0.0
Water is available only during a particular season, as much as the rice crop needs, throughout the last 5 years	73.5	26.5	0.0
The crop can rely on only one water source throughout the year to irrigate without risk	49.6	50.4	0.0
The crop can rely only on rainfall throughout the year for irrigation without risk	40.9	59.1	0.0
Water delivery information (date, time, duration) is easily accessible	28.3	53.9	17.8
Formal weather forecasts are easily accessible	74.3	25.7	0.0
Weather forecast information is used to understand rainfall and water availability for irrigating the rice crop	63.5	36.5	0.0
The farmer association discusses water availability	20.9	27.0	52.2
The farmer association discusses water sharing and water-sharing conflicts	12.6	34.8	52.6
Farmer is financially prepared for climate risk: has savings in case of crop failure	45.7	54.3	0.0
Farmer is financially prepared for climate risk: has access to a loan facility in case of crop failure	66.5	33.5	0.0
Farmer is financially prepared for climate risk: has other forms of cash reserves in case of crop failure	47.0	53.0	0.0
No family member has stopped farming due to crop failure or climate risk	50.9	49.1	0.0

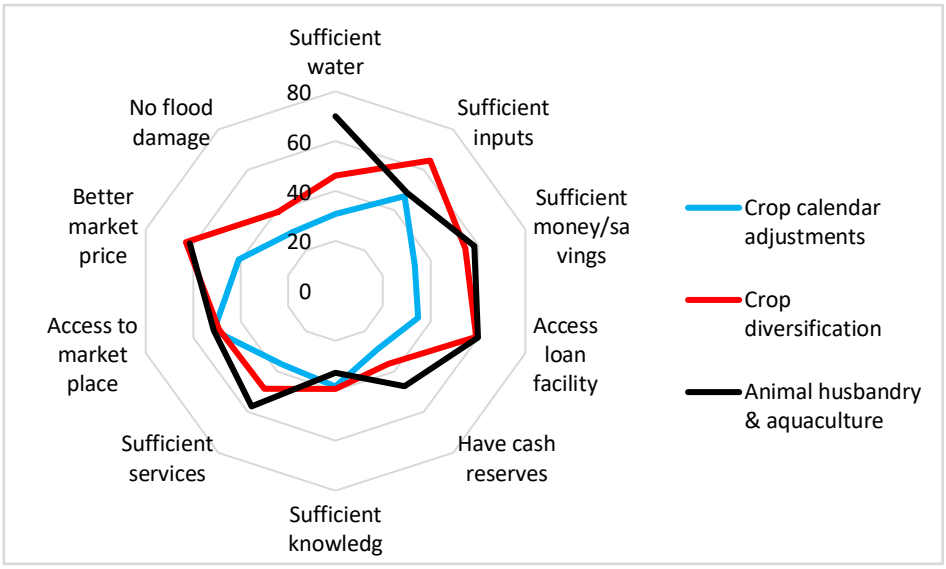
Willingness and adaptive capacity to suggested climate adaptations

Table 3 presents recommended climate adaptations per representative commune of each climate risk class. For the calculations in this section, the total number of respondents for each climate adaptation measure was considered based on their respective assigned communes.

Table 3: Suggested climate adaptations per representative commune of each climate risk class by climate smart maps

District	Commune	Suggested climate adaptation				
		Crop calendar adjustments	Crop diversi-fication	Animal husbandry & aquaculture	Irrigation infra-structure upgrades	New water source construction
Angkor Borei	Kouk thlok	X			X	
Angkor Borei	Prey phkoam	X	X		X	
Bati	Champei	X			X	
Bati	Krang Leav	X	X		X	
Bourei Cholsar	Kampong krasang		X		X	
Bourei Cholsar	Doung khpos			X	X	
Doun Kaev	Baray	X				
Kaoh Andaet	Romenh	X		X		X
Kaoh Andaet	Thlea prachum	X		X		
Kaoh Andaet	Prey Yuthka	X		X		
Kiri Vong	Prey rumdeng	X	X	X	X	
Kiri Vong	Angk prasat	X	X	X		X
Kiri Vong	Kampeaeng	X	X	X		X
Prey Kabbas	Tang Yab	X	X		X	
Prey Kabbas	Pou Rumchak	X	X		X	
Samraong	Khav		X			
Samraong	Sla		X			
Samraong	Samraong		X			
Tram Kak	Ou saray		X			
Tram Kak	Leay bour		X			
Treang	Sunlung	X				
Treang	Sambuor	X				
Treang	Angk khnor	X				

Despite being the most demanding recommendation, crop calendar adjustments are supported by only 35% of respondents. In contrast, 47% and 77% favor crop diversification and animal husbandry/aquaculture, respectively. Figure 2 illustrates the percentage of respondents—within communes assigned to each climate adaptation measure—who cited favorable factors influencing their adaptive capacity. A key observation is the variability in responses of financial resources availability for each adaptation option, reflecting farmers' diverse investment preferences and varying levels of awareness regarding the benefits of each strategy. Notably, 63–73% of respondents expressed willingness to contribute labor or financial resources toward irrigation improvements; however, limited knowledge remains a significant constraint in this area. This trend suggests that individual farmer commitment plays a more substantial role than collective action through farmer associations.



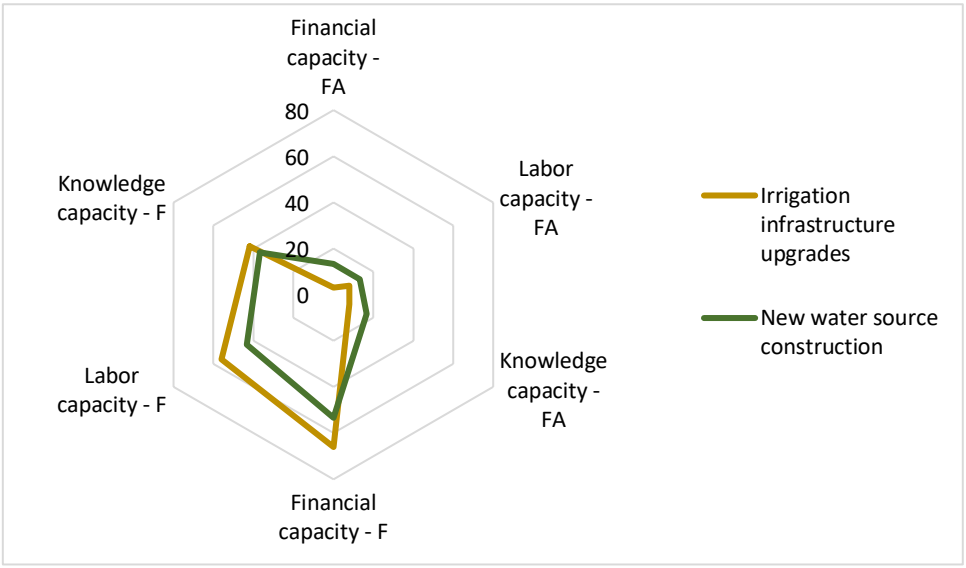


Figure 2: Percent respondents capable with influencing factors of adopting suggested climate adaptation (FA = Farmer Association; F = Farmer)

Among all adaptation strategies, animal husbandry/aquaculture and irrigation infrastructure rehabilitation emerge as potential entry points in Takeo province, as they already attract considerable support and are associated with a relatively high number of favorable enabling factors. Conversely, crop calendar adjustment remains the most challenging and capacity-intensive adaptation, requiring urgent attention. Crop

diversification, while more widely accepted, faces constraints primarily due to inadequate water availability and limited technical knowledge. Overall, knowledge gaps and financial limitations are the predominant barriers hindering effective climate adaptation in the region.

None of the farmers identified energy as a constraint, indicating a perception of water pumping as a routine or essential practice. Among the farmers who were advised to consider new water sources as part of their climate adaptation strategy, 30% proposed specific potential sources, while 20% suggested groundwater wells as the potential water source. This indicates a strong willingness to allocate resources for pumping, as it contributes to water security. The findings highlight the given importance of reliable water supply, though the energy demand is compromised. In fact, both the questionnaire and field observations confirm the widespread reliance on water pumping across the province, even from surface water sources, i.e. canals. This underscores the critical need to integrate WEF Nexus considerations into future climate adaptation and implementation plans, to ensure the sustainability and efficiency of resource use.

Lessons learnt and way forward

The findings from this study reveal a dual gap in the WEF nexus that hampers effective implementation of climate adaptations suggested by CS-Maps. The first is a gap in the implementation of climate adaptation measures, particularly where they fail to integrate cross-sectoral impacts. Strengthening the factors that influence adaptive capacity is a critical priority in this context, especially knowledge and financial capacity building. A strong agricultural extension service is essential to bridge the gap between available technological innovations and their practical adoption by farmers. The second is a limited understanding of energy demand as a controllable factor within adaptation strategies. Addressing these gaps requires a holistic approach that incorporates WEF nexus thinking into climate planning tools, particularly CS-Maps. Climate adaptation strategies should account for the interdependencies between irrigation (water), energy use, and agricultural productivity (food), ensuring that improvements in one area do not create vulnerabilities in another. This includes assessing trade-offs and synergies—such as recognizing that water pumping for agriculture (food) increases energy demand, which, if unmet, can jeopardize both water access and food production. Promoting resource-efficient technologies, like solar-powered irrigation systems, can reduce energy dependence while maintaining productivity. Equally important is policy integration that treats water, energy, and food not as isolated sectors but as interlinked systems requiring coordinated management. Furthermore, strengthening local data systems and institutional capacity is critical to designing context-specific interventions that align with actual resource flows and farmer practices. Lessons from Takeo province underscore the importance of integrated planning and offer scalable insights for building climate-resilient agricultural systems globally.

Conclusions

This study underscores a significant gap between farmers' recognition of climate risks and their ability to implement climate smart adaptation measures in Takeo province, Cambodia. Although most respondents are aware of increasing climate variability the adoption of climate-smart practices remains constrained by limited access to knowledge and financial resources. Notably, energy demand is rarely addressed in climate plans. The next phase of CS-Map implementation should focus on capacity building to enhance adaptive capacity, alongside the integration of smart energy solutions. Strengthening adaptive capacity must go beyond individual measures and embrace an integrated approach grounded in the water–energy–food (WEF) nexus with resource-efficient technologies, enhanced access to climate information, and improved institutional support. Insights from Takeo provide a valuable foundation for developing holistic, WEF-informed adaptation strategies applicable to other climate-sensitive agricultural regions.

References

D'Agostino, A. L., & Sovacool, B. K. (2011). Sewing climate-resilient seeds: Implementing climate change adaptation best practices in rural Cambodia. Mitigation and Adaptation Strategies for Global Change, 16(6), 699–720. https://doi.org/10.1007/s11027-011-9289-7

FAO. (2014). The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture. Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/3/bl496e/bl496e.pdf

IPCC. (2023a). Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157896

IPCC. (2023b). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

IRRI. (2024). Climate-Smart risk maps and adaptation plans for Cambodian Mekong Delta. International Rice Research Institute.

Kukal, M. S., & Irmak, S. (2018). Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the U.S. Great Plains Agricultural Production. Scientific Reports, 8(1), 3450. https://doi.org/10.1038/s41598-018-21848-2

Lesk, C., Anderson, W., Rigden, A., Coast, O., Jägermeyr, J., McDermid, S., Davis, K. F., & Konar, M. (2022). Compound heat and moisture extreme impacts on global crop yields under climate change. Nature Reviews Earth & Environment, 3(12), 872–889. https://doi.org/10.1038/s43017-022-00368-8

Rezaei, E. E., Webber, H., Asseng, S., Boote, K., Durand, J. L., Ewert, F., Martre, P., & MacCarthy, D. S. (2023). Climate change impacts on crop yields. Nature Reviews Earth & Environment, 4(12), 831–846. https://doi.org/10.1038/s43017-023-00491-0

Schneider, P., & Asch, F. (2020). Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. Journal of Agronomy and Crop Science, 206(4), 491–503. https://doi.org/10.1111/jac.12415

Taniushkina, D., Lukashevich, A., Shevchenko, V., Belalov, I. S., Sotiriadi, N., Narozhnaia, V., Kovalev, K., Krenke, A., Lazarichev, N., Bulkin, A., & Maximov, Y. (2024). Case study on climate change effects and food security in Southeast Asia. Scientific Reports, 14(1), 16150. https://doi.org/10.1038/s41598-024-65140-y

WBG. (2024). Climate Risk Country Profile: Cambodia. World Bank Group (WBG). https://climateknowledgeportal.worldbank.org/sites/default/files/country-profiles/16814-WB_Cambodia%20Country%20Profile-WEB.pdf

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