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Climate variability and the water-energy-food nexus in the Oti and Mono Basins, West Africa

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Abstract

This study investigates the interactions between environmental and economic variables in the Mono and Oti basins, focusing on the Water-Energy-Food (WEF) Nexus from 1980 to 2020. Using advanced machine learning and artificial intelligence techniques for statistical and graphical analysis, the study explores water intensity for food production and energy generation through scenario analysis, highlighting vulnerabilities in water and energy systems under future projections. The results reveal significant correlations between environmental variables such as rainfall, flow, energy, and agricultural yield, emphasizing the interdependence between natural resources and human activities. However, notable differences emerge between the two basins. In the Mono Basin, domestic water demand is projected to increase significantly by 2050, due to increased pressure on water resources, particularly driven by population growth and climate change impacts. In contrast, the Oti Basin, although experiencing increased water demand, remains relatively more stable due to more advanced water resource management practices and quicker adoption of technologies, particularly in irrigation and agricultural practices. Food and energy demand projections follow a similar trend, but the scenarios differ between the basins. In the Mono Basin, the Business as Usual (BAU) scenario predicts strong growth in food and energy demand, while the Technological Improvement (TI) scenario in the Oti Basin suggests a more sustainable path, primarily due to improved energy efficiency and optimized water management. The analysis of the WEF Nexus performance through composite indices also reveals significant differences between the two basins. The Mono Basin is more sensitive to changes in the water, energy, and food sectors, making it more vulnerable to climate change impacts and human pressures. On the other hand, the Oti Basin shows higher resilience, largely due to more integrated policies and practices. Finally, the study proposes a sustainability index that combines economic, environmental, and social factors to assess long-term resource management sustainability. This highlights the need for integrated and cross-sectoral policies that should be tailored to the specific contexts of both basins to ensure the resilience and sustainability of resource systems in the Mono and Oti basins.

keywords: Environmental and economic variables; Water-Energy-Food Nexus; Mono-Oti River basins

1. Introduction

In sub-Saharan Africa, exposure and vulnerability to climate risks are notably high across critical economic sectors. Extreme events, such as droughts and floods, have highlighted the scale of disruption (Ali & Lebel 2009; Bodian 2014). For instance, the prolonged drought from 1968 to 1995 in West Africa exemplified the cascading impacts, including widespread food insecurity, power outages, and drinking water shortages, which disproportionately affected small and medium-sized enterprises. Although economic development can reduce poverty and dependency on climate-sensitive

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agriculture, vulnerability to climate shocks is likely to remain elevated in tropical regions as assets and economies expand.

As these climate risks intensify, global challenges such as population growth and urbanization further strain critical nexus resources. In sub-Saharan Africa, the demand for these resources is expected to increase significantly, with nations struggling to meet the rising demand for already scarce resources in a sustainable manner (Van Ittersum et al. 2016). Many developing countries, face considerable disparities in access to vital resources like water, leaving millions without sufficient supply (Rasul & Sharma, 2016; Finley et al., 2014). The impacts of climate variability, such as decreased rainfall reliability and increased water demand are especially pronounced in sectors like agriculture and energy production, which are essential to several national development agendas (Endo et al. 2015; Gebreyes et al. 2020). According to Ferroukhi et al. (2015), by 2050, global energy demand is projected to double, while water and food demand will increase by 50%, driven by the need to support an anticipated population of 9 billion people

Given the increasing pressure on essential resources like water, food, and energy, sustainable management has become crucial for building resilience in regions most vulnerable to these challenges (Pimentel et al. 2010; Ringler et al. 2013). Similarly, the food sector demands significant amounts of water and energy in its operations. Additionally, food has been utilized as a raw material in biofuel production for both domestic and industrial purposes (Fig. 1). These inherent interdependencies create a complex web of connections between water, energy, and food resources. The Water-Energy-Food (WEF) nexus offers a comprehensive conceptual framework and approach to tackling the intricate and multifaceted relationships involved in the development of these vital resources. The WEF nexus framework offers a holistic approach to understanding the complex interdependencies and trade-offs among these vital resources (Liu et al. 2017; Wang et al. 2018; Mohtar et al. 2016). This framework has gained attention as an effective strategy to achieve sustainable development goals and promote a green economy, following its introduction at the Bonn Nexus Conference in 2011 (Martin-Nagle et al. 2023).

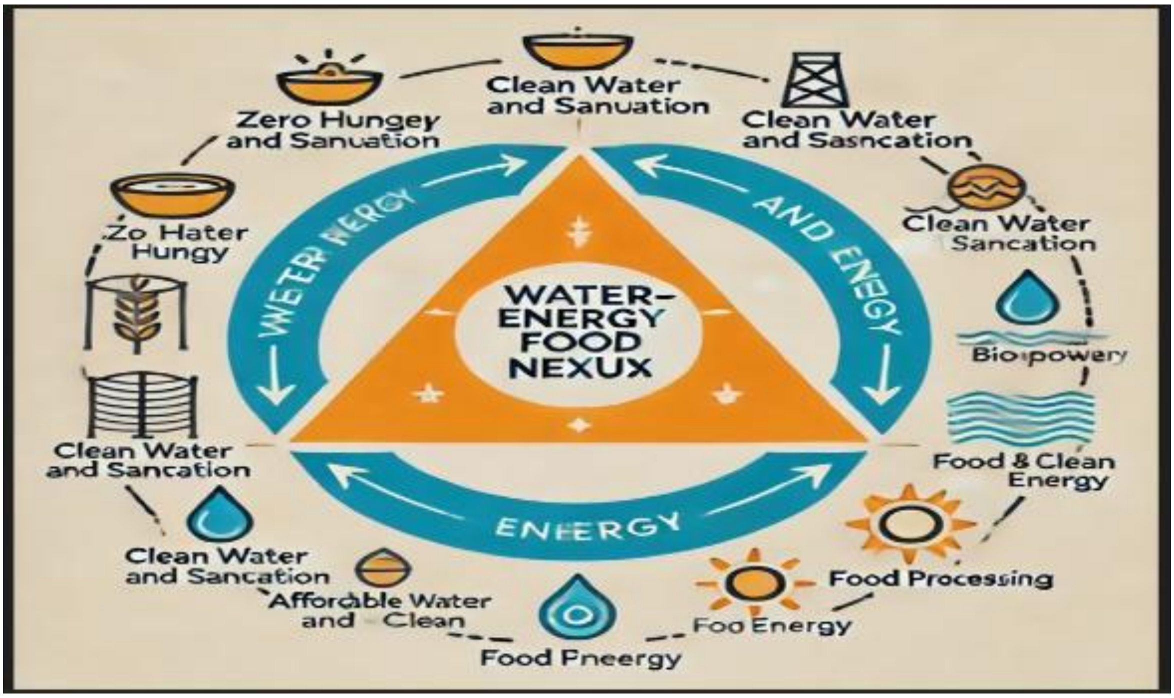

Figure 1 Interlinkages between Sustainable Development Goals of water, energy and food

The nexus approach has since evolved to incorporate additional factors, such as climate change, into its scope, making it a valuable tool for supporting food security and sustainable development in sectors like agriculture (UNECE 2017). According to the FAO (2014), the nexus approach addresses crucial sustainability goals, including zero hunger (SDG2), clean water and sanitation (SDG6), and affordable clean energy (SDG7) (Senzanje et al. 2022).

Recent research has highlighted the importance of integrating LWEF nexus considerations into policy and planning frameworks. For instance, Andrews-Speed et al. (2023) emphasize that a comprehensive approach to resource management can strengthen community resilience to environmental stressors and improve their adaptive capacity.

Additionally, Middleton et al. (2012) argue that effective management of the nexus can lead to more equitable resource distribution, thereby enhancing livelihoods and reducing vulnerabilities in vulnerable regions like west Africa.

In West and Central Africa, institutions such as the Niger Basin Nexus Dialogue have promoted the WEF nexus to guide the integrated management of transboundary resources and design policies aimed at holistically addressing development objectives. These initiatives seek to enhance resource efficiency in tackling pressing issues such as food insecurity, poverty, and unpredictable rainfall patterns, which impact both agricultural productivity and energy production (Senzanje et al. 2022). However, WEF-related research remains minimal in the West African context. It is therefore essential to conduct more studies in this domain to better understand the complex interdependencies between water, energy, and food resources in the region. Such research is fundamental to developing effective strategies for sustainable resource management, addressing vulnerabilities, and enhancing resilience against climate change and socio-economic challenges in West Africa.

The Mono Basin and Oti Basins, located in West Africa, exemplifies the critical need for integrated management of LWEF resources. these Basins are a vital ecological and economic zone that faces significant challenges related to water scarcity, land degradation, and food insecurity, all exacerbated by climate variability and socio-economic pressures (Ernest et al. 2015, Lawin et al. 2019, Lamboni et al. 2019, Lamboni et al. 2024). Addressing these challenges requires a deep understanding of how climate, water, energy, and food systems interact and affect one another, especially in the context of regional livelihoods.

The primary objective of this study is to assess the Water-Energy-Food (WEF) nexus and its impact on local livelihoods in the Mono and Oti Basins through a scenario-based analysis. Specifically, the study aims to:

- Evaluate water intensity across sectors (agriculture, energy, and domestic use) to determine the competing demands and allocation efficiency within the WEF nexus.
- Identify key vulnerabilities associated with climate variability, resource scarcity, and socio-economic factors, impacting sustainable development in the region.
- Develop and apply sustainability indices to quantify the resilience and adaptability of the WEF nexus to current and future challenges.
- Analyze potential scenarios under varying environmental, economic, and policy conditions to propose actionable strategies for improving resource management and supporting livelihoods.

The results will provide a framework for policymakers, researchers, and stakeholders to enhance sustainable practices, reduce vulnerabilities, and foster integrated resource management in the Mono and Oti Basins.

2. Materials and Methods

2.1. Study area

The Mono and Oti River Basins, situated in West Africa (Fig. 2), offer a distinctive framework for analyzing the interplay of Land, Water, Energy, and Food (LWEF) nexus resources. Both basins are transboundary systems where communities rely heavily on natural resources for their livelihoods, particularly through agriculture, fishing, and energy production. A comparative study of these two basins not only highlights the unique challenges of each but also enables a broader understanding of LWEF nexus dynamics, addressing critical issues related to climate change, population pressure, and sustainable resource management.

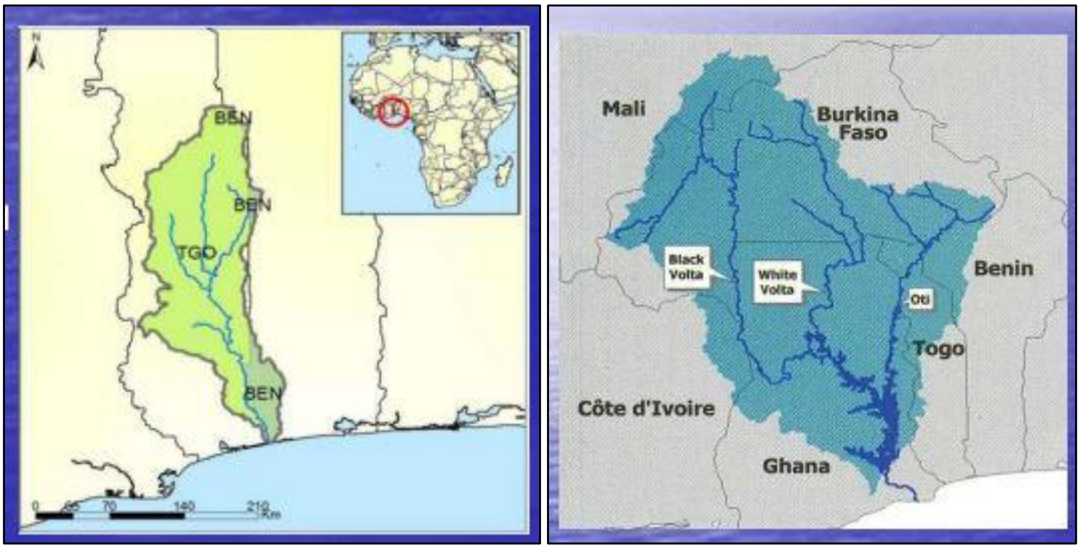

Figure 2 Study area

The Mono River Basin, shared by Togo and Benin, covers an area of approximately 25,400 km^2 and lies between 06°16' and 09°20' N and 0°42' and 2°25' E (Lamboni et al., 2024). Its topography ranges from highlands to coastal plains, and its tropical climate is shaped by its proximity to the equator. The basin exhibits diverse soil types, with more fertile lands concentrated in the south and less productive soils in the northern regions. The Mono River serves as a crucial freshwater source, supporting both agriculture and other natural resource-based activities. The basin experiences a bimodal rainfall pattern in the south (with rainy seasons from March to July and from September to November), while the northern region has a unimodal pattern, with a single rainy season from May to October. These seasonal variations critically influence water availability for agricultural activities, domestic usage, and energy production. However, climate change has exacerbated the variability in rainfall and river flow, leading to increased instances of droughts and floods, which adversely impact agricultural yields and livelihoods. The basin is home to over two million inhabitants, with a population growth rate of 2.9% annually (WAEMU, 2006). The local economy is predominantly based on agriculture, fishing, and energy generation, with the Nangbéto Hydroelectric Dam being a vital infrastructure that supplies electricity to both Togo and Benin. Despite this, the region faces persistent challenges such as limited access to potable water, inadequate renewable energy infrastructure, and recurrent food insecurity. In this context, the LWEF nexus plays a pivotal role in ensuring food security and sustainable development. A strategic approach to managing these resources is essential for enhancing resilience against environmental and socio-economic pressures, as well as mitigating the impacts of climate variability and population growth on the basin’s ecosystems and communities.

The Volta River Basin, located between 5°30' N and 14°30' N and 2°00' E and 5°30' W, spans approximately 400,000 km^2 and traverses six West African countries: Ghana, Burkina Faso, Togo, Benin, Côte d'Ivoire, and Mali. It is one of the most significant river systems in the region, fed by major tributaries including the Black Volta, White Volta, and Oti rivers, which play a central role in the provision of water for irrigation, drinking, and energy production. The Akosombo Dam, located on the Volta River in Ghana, is a key infrastructure providing hydroelectric power to Ghana and its neighboring countries. The Volta Basin is home to an estimated 19 million people, with a population growth rate of 2.5% (FNUAP, 2007). This study focuses on Oti River Basin (ORB), which represents the Togolese portion of the Volta River Basin. Covering an area of 26,700 km^2, equivalent to about 47.3% of Togo's total surface area, the ORB is situated between latitudes 6°10' and 11°10' N and longitudes 0° and 1°25' E. Similar to the Mono Basin, the communities within the Oti River Basin heavily depend on water resources for agriculture and energy production. However, the Volta Basin faces more complex challenges in resource management due to its larger geographic scale and the involvement of multiple countries. The Volta Basin Authority (VBA) plays a critical role in transboundary water governance, facilitating cooperation and ensuring the sustainable management of water resources across the basin. The impacts of climate change, such as irregular rainfall patterns and reduced river flows, increasingly affect food security and energy production in the region. Coordinated efforts among the basin countries are essential to tackle these challenges and ensure sustainable livelihoods.

The comparative analysis of the Mono and Oti Rivers Basins reveals both shared and distinct challenges in managing the WEF nexus. Both basins rely heavily on water resources for agriculture, energy production, and domestic use, yet their management strategies differ due to their varying sizes and geopolitical complexities. By comparing the WEF nexus dynamics in these two basins, this study aims to provide insights into the similarities and differences in resource management approaches across diverse ecological, geographical, and institutional contexts. This comparative framework not only deepens the understanding of sustainable resource management in West Africa but also offers lessons that can be applied to other transboundary river basins worldwide, where integrated solutions are needed to address the growing challenges of climate change, sustainable development, and resource security.

2.2. Data Collection and Sampling Techniques

The collection of socio-economic and environmental data is essential for understanding the interactions between environmental factors and local livelihoods. It provides a foundation for assessing the impacts of climate change on agriculture, energy, and water access, while supporting the development of adaptive management strategies (Deressa et al., 2009; Mendelsohn et al., 2000). Data collection follows a structured framework, as presented in the table below, ensuring comprehensive coverage of key Water-Energy-Food (WEF) nexus sectors and their spatial extent.

Table 1 Description and sources of data.

Description	Source	WEF Sector/Interaction	Spatial Extent
Food production and cropping area	SRID-MoFA	Food	National estimates
Water abstraction data	Water Resources Commission (WRC)	All sectors, including domestic	National
Water abstraction and food production data	GIDA-Kpong Irrigation Scheme, 2019	Water for Food	Kpong Irrigation Scheme
Water abstraction data for hydropower	Volta River and Mono River Authorities	Water for Energy	Akosombo and Kpong hydropower stations
Energy production data	Volta River and Mono River Authorities	Energy	Nangbéto hydropower station
Annual rainfall data	Meteorological Agencies of Benin and Togo	Water	National: Agroecological Zones

Field surveys conducted with local farmers will gather information on agricultural income, crop types, yields, and the impacts of climate variability on productivity. This help identify areas most vulnerable to climatic fluctuations and support policies aimed at enhancing agricultural resilience in response to climate change. Furthermore, water abstraction data for hydropower collected from the Volta River and Mono River Authorities cover key sites such as the Akosombo and Nangbeto hydropower stations. Meanwhile, annual rainfall data from the Meteorological Agencies of Benin and Togo provide critical insights into water availability across various agroecological zones. Additionally, energy production data, including hydropower generation at Nangbeto, is collected from the Volta River and Mono River Authorities to evaluate energy sustainability and its interactions with water resources. The analysis was conducted using machine learning and artificial intelligence techniques, which provide advanced statistical and graphical capabilities.

2.2.1. Identification of Analytical Scenarios

To evaluate the future impacts of climatic and socio-economic variations, scenarios will be defined to represent potential contexts based on specific assumptions under three overarching scenarios: Business as Usual (BAU), Technological Improvement (TI), and Climate Change (CC) (Deressa et al., 2009; Mendelsohn et al., 2000). In the Business as Usual (BAU) scenario, the current trends in climate, agricultural practices, and energy use will be maintained without significant policy or technological interventions. This baseline will serve as a reference point for evaluating the impacts of maintaining the status quo on the LWEF system and livelihoods. The Technological Improvement (TI) scenario will explore the integration of advanced technologies to enhance resource efficiency and resilience. For example, hybrid energy systems combining hydropower turbines and photovoltaic panels will be analyzed to assess their potential for increasing energy security during periods of low water availability (IPCC, 2014). Similarly, sustainable agricultural practices, such as efficient irrigation systems and conservation agriculture, will be examined for their ability to boost productivity and improve natural resource management.

The Climate Change (CC) scenario will focus on the impacts of climatic variability, with specific sub-scenarios addressing potential extreme conditions. An extended dry season scenario will evaluate the consequences of prolonged droughts on agriculture, hydrology, and energy supply, while an excessive rainy season scenario will study the effects of heavy rainfall and flooding on agricultural infrastructure, irrigation systems, energy installations, and local livelihoods. By combining these overarching scenarios, the study will provide a robust framework for understanding the implications of different development pathways on the Water-Energy-Food (WEF) nexus in the Mono and Oti basins, enabling the identification of adaptive strategies for sustainable resource management.

2.3. Water Intensity Analysis for Food Production and Energy Generation

Water intensity is a measure that quantifies water consumption per unit of output in agricultural and energy sectors. It can be defined by the following equations:

For the agriculture sector:

$$\text{Agricultural Water Intensity} = \frac{\text{Total Volume of Water Used in Agriculture}}{\textit{Total Food Production}} \quad (1)$$

For the energy sector:

$$\text{Energy Water Intensity} = \frac{\text{Total Volume of Water Used for Energy}}{\textit{Amount of Energy produced}} \quad (2)$$

These calculations will be applied under different scenarios (Business As Usual - BAU, Technological Innovation-TI, and Climate Change-CC) to estimate the impacts of various policies or technological innovations on water use efficiency. According to Liu et al. (2011), these ratios allow for a comparison of efficiency across different production systems and for identifying potential efficiency gains through technological innovation.

2.4. Water and Energy vulnerability and sustainability indices

To assess the vulnerability of water and energy resources, vulnerability indices are used based on climate factors, consumption trends, and local challenges. Let X_1, X_2,...,X_n represent the different factors contributing to vulnerability, such as rainfall, energy availability, water flow, evapotranspiration, etc. Each of these factors can be normalized to bring them into a common scale, typically between 0 and 1

$$\text{Normalization:} X^i_{norma} = \frac{X^i - min(X^i)}{max(X^i) - min(X^i)} \quad \ldots\ldots\ldots \quad (3)$$

X^i is the original value of the i^{th} factor, min(X^i) and max(X^i) are the minimum and maximum values of the i^{th} factor across the dataset.

$$\text{Vulnerability Index (VI) is:} VI = \sum_i^n w_i f(X^i_{norma}) \quad \ldots\ldots\ldots (4)$$

$$\text{Sustainability Index (SI) is: } SI = \sum_i^n w_i \text{ Normalized Indicator } \ldots\ldots\ldots \ \mathit{(5)}$$

w_i is the weight assigned to the i^{th} factor, reflecting its relative importance in the calculation of the vulnerability index. f(X^i_{norma}) is a function applied to the normalized value of the i^{th} factor.(Liu et al. 2022).

2.5. Study of Correlations Between Environmental and Economic Variables

When calculating the **correlation matrix** between multiple variables, each pair of variables will have its own correlation coefficient. For a dataset with multiple variables, say X_1, X_2,..., X_n, the **correlation matrix** shows the Pearson correlation between every pair of these variables.

$$\text{The correlation matrix R is defined as: } R = \begin{pmatrix} 1 & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & 1 \end{pmatrix} \ldots\ldots\ldots \quad (6)$$

where: r_{ij} is the Pearson correlation coefficient between variables X_i and X_j, the diagonal elements are always 1 because the correlation of a variable with itself is 1. Each element r_{ij} is calculated using the Pearson correlation formula:

$$r_{ij} = \frac{\sum_i^n (X_i - X_{im})(X_j - X_{jm})}{\sqrt{\sum (X_i - X_{im})^2}\sqrt{\sum (X_j - X_{jm})^2}} \quad \text{..... (7)}$$

2.6. Calculation of Composite Indices for the WEF Nexus

To analyze the Water-Energy-Food (WEF) nexus, selecting robust global indicators is essential (Rydin et al. 2003). In water resources, indicators like water availability, water quality (using metrics such as Biological Oxygen Demand (BOD) and Total Dissolved Solids (TDS)), and water consumption patterns are vital. These variables assess water security, especially amid climate variability, as noted by Falkenmark and Rockström (2004). For energy, indicators like access to renewable and non-renewable sources and energy consumption per capita play a significant role in supporting agricultural productivity. According to IEA (2019), disparities in energy access remain a challenge, especially in developing regions. Finally, food security indicators, such as crop yield, food access, and availability, are essential for evaluating agricultural effectiveness in meeting nutritional needs (Estoque et al. 2019; Mazziotta & Pareto, 2019). Godfray et al. (2010) stress that integrating land, water, and energy resources is vital for food security. Using datasets from the FAO and World Bank provides a strong foundation for evaluating the LWEF nexus and informs policy strategies to mitigate resource depletion and climate change impacts.

To establish **WEF (Water-Energy-Food) nexus indicators** and calculate the nexus values, we'll typically follow these steps, which involve creating a composite indicator or index for each resource (Water, Energy, and Food). We base these indices on selected indicators and use a weighted approach (such as Analytical Hierarchy Process (AHP), normalization techniques, or statistical aggregation) to combine them.

To begin with, data normalization is crucial to bring different units into a comparable scale, ensuring that no single indicator disproportionately influences the results. One common approach is Min-Max Scaling, which adjusts the values to a range between 0 and 1. The equation for Min-Max Scaling is:

$$\boldsymbol{X = \frac{X_0 - X_{min}}{X_{max} - X_{min}}} \quad \text{......... } \mathbf{(8)}$$

Where X_0 represents the original value, and X_{min} and X_{max} are the minimum and maximum values of each indicator, respectively. This scaling facilitates a direct comparison between indicators, enabling an unbiased analysis of their relative importance.

Next, to **weight the normalized indicators,** we can utilize methods such as the **Analytical Hierarchy Process (AHP).** AHP assigns importance to different indicators based on expert judgments or specific criteria. Let's denote the weight matrix as W, where individual weights correspond to indicators such as W_{Land}, W_{Water}, etc. These weights reflect the relative significance of each indicator in the overall composite calculation (Mabhaudhi et al. 2019).

After determining the weights, we move to the composite indicator calculation. The composite index for each resource is computed as the weighted sum of its normalized indicators**:**

$$I_R = \sum_i^n W_i X_i \quad \text{......... (9)}$$

Here, I_R represents the composite index for a given resource (such as Food, Water, or Energy), W_i is the assigned weight for the i^{-th} indicator, and X_i is the normalized value of that indicator. This approach ensures that the most critical indicators (as determined by the weights) contribute proportionally to the overall score, providing a comprehensive assessment of each resource.

The Consistency Index (CI) and Consistency Ratio (CR) are critical in determining whether the pairwise comparisons in the AHP matrix are consistent enough for reliable decision-making.

The Consistency Index (CI) is used to measure how consistent the pairwise comparisons are. Its formula is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{......... (10)}$$

Where: λ_{max} is the largest eigenvalue of the comparison matrix, n is the number of criteria (the order of the matrix).

The Consistency Ratio (CR) is calculated by comparing the Consistency Index (CI) with a Random Index (RI), which is a table of random consistency indices based on matrix size. The formula is:

$$CR = \frac{CI}{RI} \quad \text{..............} (11)$$

we computed CI using the formula;

$$CI = \omega - \frac{n}{n-1} \quad \text{........} (12)$$

where n represents the number of indicators and ω represent the value obtained from the weight value of indicator.

2.7. Overall Performance Analysis of the WEF Nexus on Livelihoods

The impact of the WEF Nexus on livelihoods is evaluated by measuring economic and well-being indicators, such as income and access to essential services. Normalized scores can be used for each indicator and combined as follows:

$$PLWEF = \alpha \times Income + \beta \times Access\ to\ Drinking\ Water + \gamma \times Food\ Security \quad \text{.........} (13)$$

where α, β, and γ are the weights of each indicator, determined according to their importance for the local population (Hanjra and Qureshi, 2010).

2.8. Evaluating the Sustainability of the WEF Nexus Over Time

To assess sustainability, a sustainability index SWEF can be calculated, combining economic, environmental, and social factors:

$$SWEF = \delta \times Sectoral\ GDP + \theta \times Ecological\ Footprint + \lambda \times Well\text{-}being\ Index \quad \text{.........} (14)$$

where δ, θ, and λ are weighting coefficients. These coefficients can be adjusted according to local priorities and future projections, and this index can be calculated at regular intervals to track sustainability trends over time (Allan et al., 2015).

2.9. Modeling Tools

Tools such as R, Python, and ArcGIS are used to model the scenarios. These tools will enable the simulation of time series data for climatic and socio-economic variables to estimate the impact of various scenarios on the sustainability of the WEF Nexus. The results were analyzed to identify vulnerabilities and opportunities to improve the integrated management of water, energy, and food in the region. Through this approach, adaptation strategies can be proposed to mitigate the risks associated with environmental changes.

3. Result

3.1. Characterization of interactions between environmental and economic variables

The characterization of interactions between environmental and economic variables highlights the complex dynamics and mutual dependencies shaping resource management and economic development. The Fig 3 and Fig 4 highlight the interconnectedness between precipitation, river flow, hydroelectric power production, and agricultural yields from 2000 to 2022.

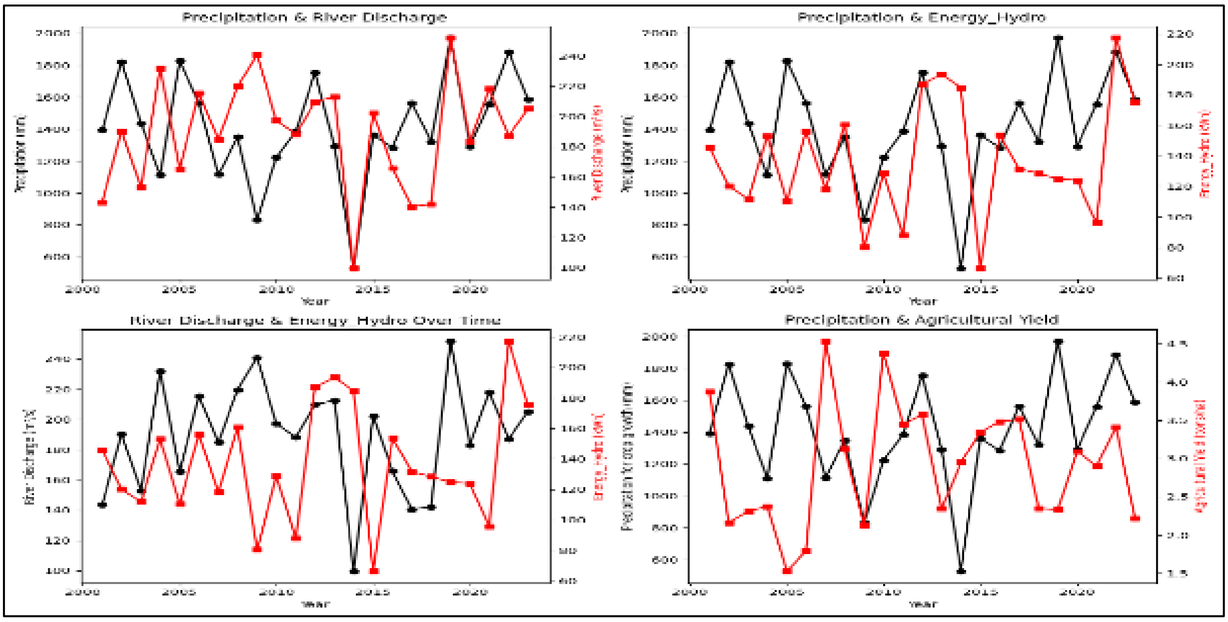

Figure 3 Plot of average precipitation, plant discharge, agricultural yields, and energy production at Nangbeto dam. The average precipitation of the Mono Basin was estimated using the Thiessen Method

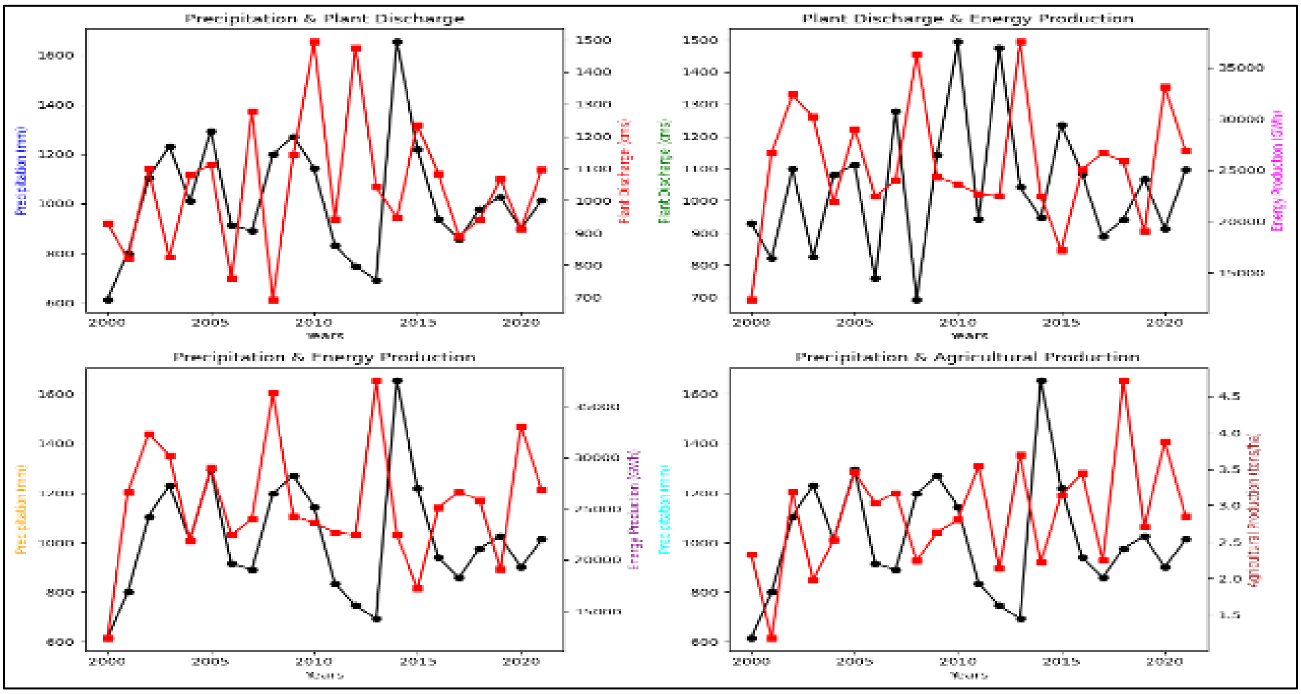

Figure 4 Plot of average precipitation, plant discharge, agricultural yields, and energy production at Akosombo dam. The average precipitation of the oti Basin was estimated using the Thiessen Method

A direct correlation is evident between precipitation and river flow in the first graph, where years of heavy rainfall lead to higher river flow. This connection is mirrored in the third graph, showing that hydroelectric power production strongly depends on river flow, with energy output fluctuating in line with water availability. The correlation between precipitation and agricultural yields in the fourth graph also emphasizes water's critical role in agriculture, although anomalies show that other factors can disrupt this link. The comparison between the two basins reveals both similarities and differences in the relationships between precipitation, river flow, energy production, and agricultural yields. In both basins, precipitation directly correlates with river flow-wet years see increased river discharge. This link underscores the rainfall-dependence of water systems in both basins. Similarly, hydroelectric power generation is heavily influenced by river flow, with more water leading to higher energy output, especially in wet years like 2010 and 2015. Both basins show the importance of rain-fed agriculture, where higher precipitation supports better crop yields. However, the Oti Basin shows greater sensitivity to rainfall fluctuations. Its plant discharge and agricultural yields vary more dramatically, suggesting lower water storage capacity or catchment vulnerabilities. Additionally, the Oti Basin has anomalies in energy production, where high plant discharge does not always translate to increased output, likely due to management inefficiencies. In contrast, the first basin exhibits a more stable relationship between water flow and energy generation, indicating better infrastructure.

3.2. Water intensity for food production and energy generation under scenario analysis

Water intensity for food production and energy generation is analyzed under different scenarios to assess resource efficiency and sustainability in meeting future demands. The bar plots (Fig 5 and Fig 6 below) compare water intensity for food production and energy generation in the Mono and Oti Basins from 2020 to 2050 under three scenarios: Business as Usual (BAU), Technological Improvement (TI), and Climate Change (CC). For food production under BAU, the Oti Basin has a higher water intensity (~1000 m^3/ton) than the Mono Basin (~900 m^3/ton), suggesting that even under current conditions, the Oti Basin requires more water. When technological improvements are applied, both basins see reductions, with the Mono Basin dropping to ~700 m^3/ton and the Oti Basin to ~800 m^3/ton, showing the potential of technology to lower water demand. However, under the climate change scenario, water intensity increases sharply in both basins, with the Mono Basin reaching ~1100 m^3/ton and the Oti Basin nearly ~1200 m^3/ton, highlighting the greater vulnerability of the Oti Basin to climate impacts. Similarly, in the energy sector under BAU, the Mono Basin shows lower water intensity (~1.5 m^3/kWh) than the Oti Basin (~2.0 m^3/kWh). Technological improvements reduce water intensity to ~1.0 m^3/kWh in the Mono Basin and ~1.5 m^3/kWh in the Oti Basin.

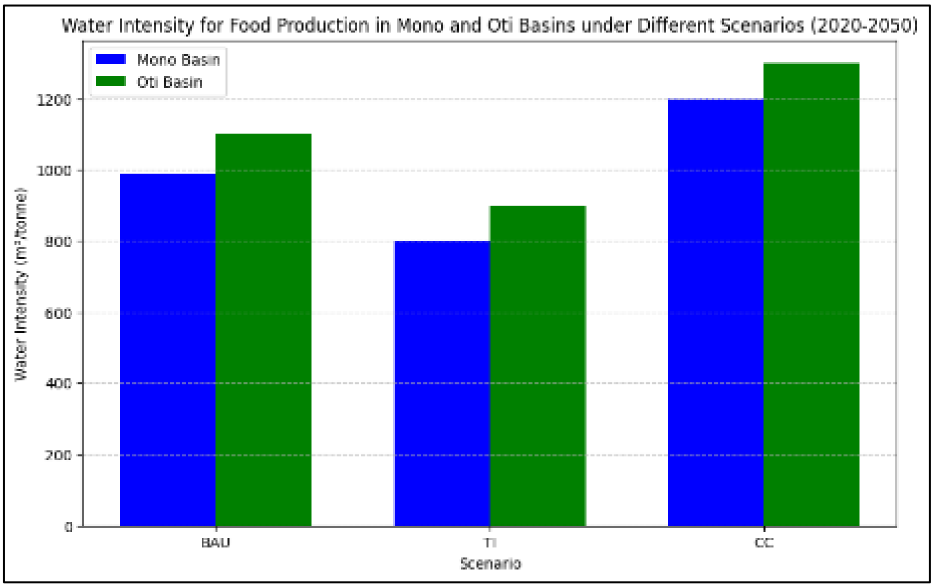

Figure 5 Water intensity of food production in Mono and Oti basin

However, under climate change, both basins experience significant increases, with the Mono Basin rising to ~1.8 m^3/kWh and the Oti Basin to ~2.5 m^3/kWh, again showing the Oti Basin's heightened vulnerability, especially in energy generation. Comparatively, these trends align with studies conducted in Ghana, particularly in regions with arid climates. For instance, in Ghana's northern regions, agricultural water intensity is higher due to inefficient irrigation systems, as seen in the Oti Basin. Studies like Quaye (2008) and Chang et al. (2016) underscore similar inefficiencies, leading to increased water consumption, which mirrors our findings. Additionally, technological advancements in Ghana have been shown to reduce water demand, aligning with the TI scenario in our study. However, under climate change, both regions-Ghana and the Oti Basin show similar trends of increased water intensity for agriculture, as documented by Mekonnen and Hoekstra (2011). Moreover, while the water intensity for energy production in our study basins remains lower than in Ghana's Kpong dam, where it reaches up to 35 m^3/kWh, the increase under the Climatic Change scenario emphasizes the vulnerability of the energy sector to climate change, particularly in the Oti Basin. This comparative analysis with Ghana highlights the shared challenges of water resource management in West Africa, reinforcing the importance of adaptive policies to mitigate climate impacts.

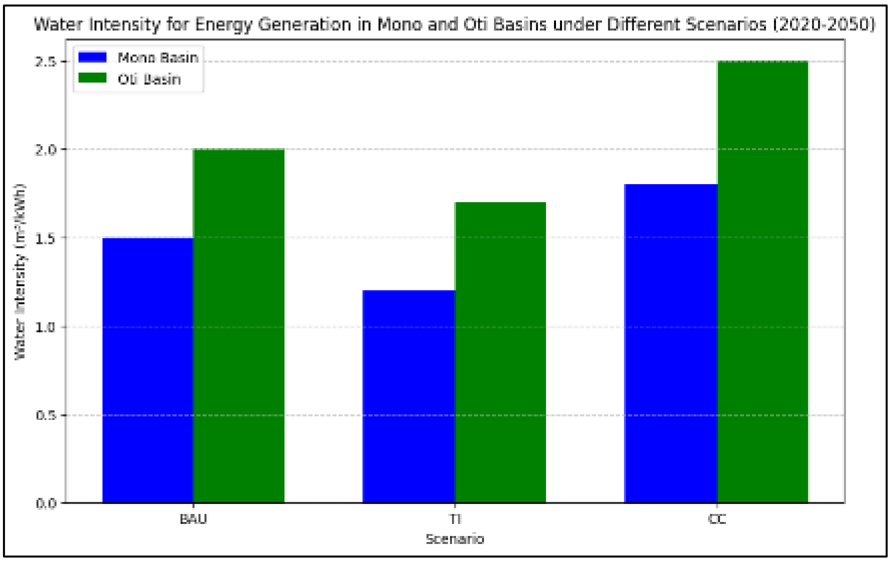

Figure 6 Water intensity of energy production in Mono and Oti basin

3.3. Energy and water vulnerability over mono basin

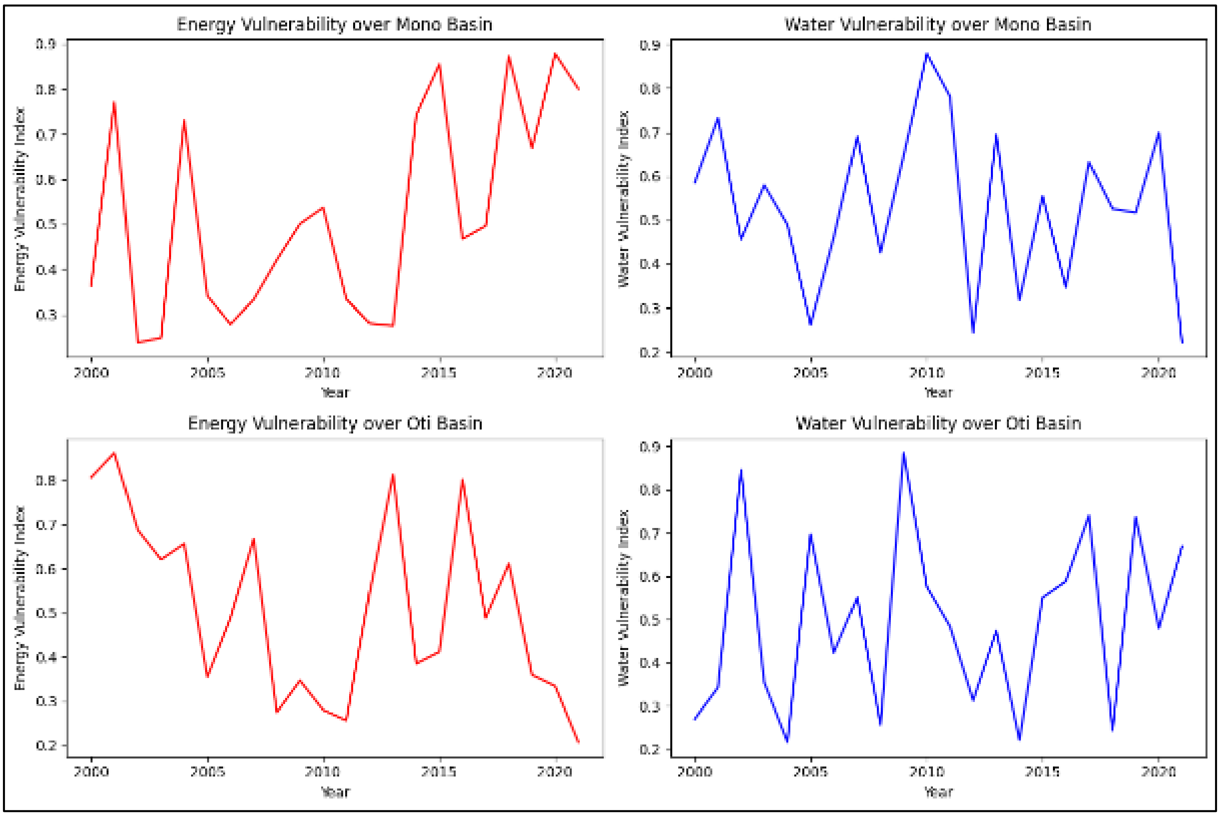

Figure 7 Energy and Water Vulnerability Indices

Understanding the evolution of energy and water vulnerabilities in the Mono and Oti Basins is crucial for developing effective strategies to manage resources and mitigate risks in these regions. The graphs (Fig 7) illustrate the evolution of energy and water vulnerability in the Mono and Oti basins between 2000 and 2022. Between 2000 and 2020, the Mono and Oti Basins exhibited distinct trajectories in energy and water vulnerability, as reflected in the numerical trends. In the Mono Basin, the energy vulnerability index fluctuated between 0.3 and 0.9, showing a significant rise over the years, with notable peaks around 2010 and 2020 reaching as high as 0.9. Meanwhile, the water vulnerability index ranged between 0.3 and 0.8, with no clear trend, but with significant peaks around 2010 and 2015, indicating persistent instability in water resources. In contrast, the Oti Basin followed a different pattern. The energy vulnerability index, starting near 0.8 in the early 2000s, gradually decreased, reaching its lowest point of 0.2 around 2020. However, the water vulnerability index for the Oti Basin fluctuated between 0.3 and 0.8, similar to the Mono Basin, with no clear long-term trend, showing peaks in the early 2000s, 2010, and 2020.This variability suggests that the basin also experiences significant periods of water stress, likely caused by climatic irregularities such as droughts or floods, as well as human factors, such as ineffective water management (Lamboni et al.2024).

3.4. Future water demand projections under scenario analysis

Understanding the projected domestic water demand in the Mono and Oti Basins under different scenarios is crucial for shaping future water management policies. These insights provide a roadmap for strategic planning, especially in light of potential technological advancements and the profound impacts of climate change on water resources. The graph (Fig 8) illustrates the projected domestic water demand in the Mono and Oti basins under three different scenarios from 2020 to 2050. The scenarios depicted are BAU (Business As Usual), TI (Technological Innovation), and CC (Climate Change), with water demand measured in billion cubic meters. Starting with the Mono Basin, we observe that the Mono-BAU scenario shows a steady increase in water demand. The demand starts at around 1 billion cubic meters in 2020 and rises to approximately 1.4 billion cubic meters by 2050. This indicates a consistent growth in water demand without any significant changes in policy or technology, which could reflect growing population and economic activities. In contrast, under the Mono-TI scenario, the demand is slightly lower. Beginning at about 0.9 billion cubic meters in 2020, it increases to around 1.3 billion cubic meters by 2050. This suggests that technological innovations, such as water-saving technologies or improved water management practices, help reduce the rate of water demand growth. These innovations appear to offset some of the pressures seen in the BAU scenario. Interestingly, the Mono-CC scenario shows even slower growth in water demand. Starting just below 1 billion cubic meters in 2020, it rises to only around 1.2 billion cubic meters by 2050. This slower growth could be attributed to the impact of climate change, possibly resulting in reduced water availability or altered consumption behaviors. As a result, the Mono Basin under climate change scenarios may experience moderated demand growth compared to business-as-usual trends.

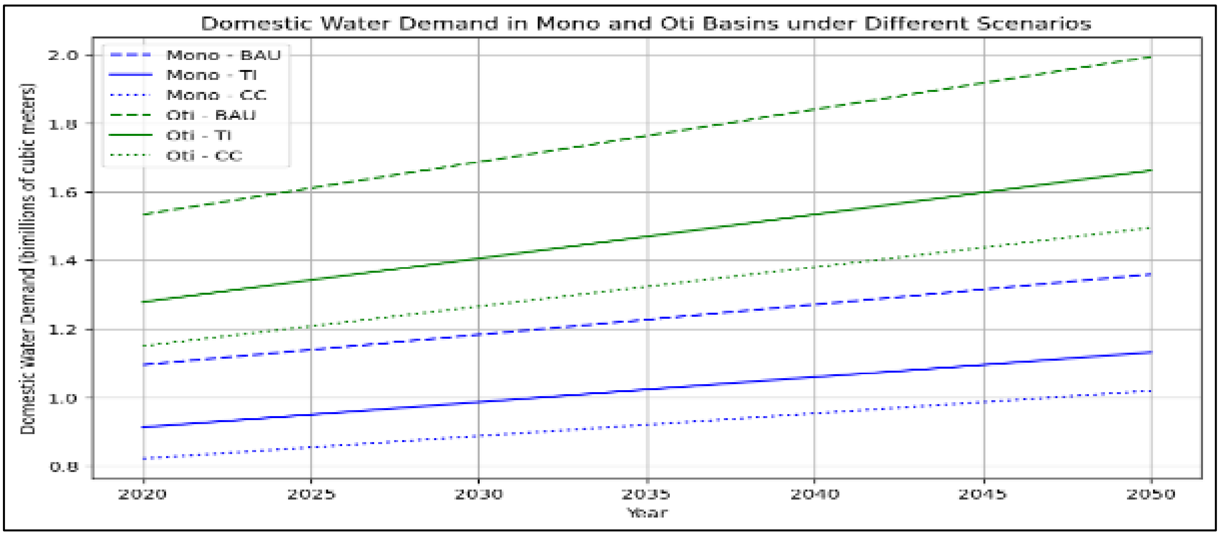

Figure 8 Future water demand projections under scenario analysis

Shifting focus to the Oti Basin, we notice a higher overall demand. In the Oti-BAU scenario, water demand grows significantly, from around 1.2 billion cubic meters in 2020 to nearly 2 billion cubic meters by 2050. The steeper increase compared to the Mono Basin suggests that the Oti Basin faces greater domestic water demand pressures under a business-as-usual scenario, potentially driven by higher population growth or more intensive economic activities. Under the Oti-TI scenario, the demand rises from about 1.1 billion cubic meters in 2020 to approximately 1.7 billion cubic meters by 2050. Similar to the Mono Basin, technological innovations seem to reduce demand, albeit at a slower rate compared to BAU. These innovations may include advances in water-efficient technologies and practices that lower overall consumption. Finally, the Oti-CC scenario shows the slowest growth in water demand for the Oti Basin. Starting at about 1.1 billion cubic meters in 2020, the demand increases more modestly to around 1.5 billion cubic meters by 2050. This reflects the impact of climate change, potentially limiting water resources or altering water use patterns, which may, in turn, dampen the rise in water demand compared to the BAU scenario.

3.5. Future food and energy demand projections under scenario analysis

The graphs (Fig 9) analyze domestic food demand (left) and domestic energy demand (right) in the Mono and Oti basins from 2020 to 2050, based on the Business as Usual (BAU) and Technological Improvement (TI) scenarios. These results are based on projections derived from national reports and studies specific to the water basins.

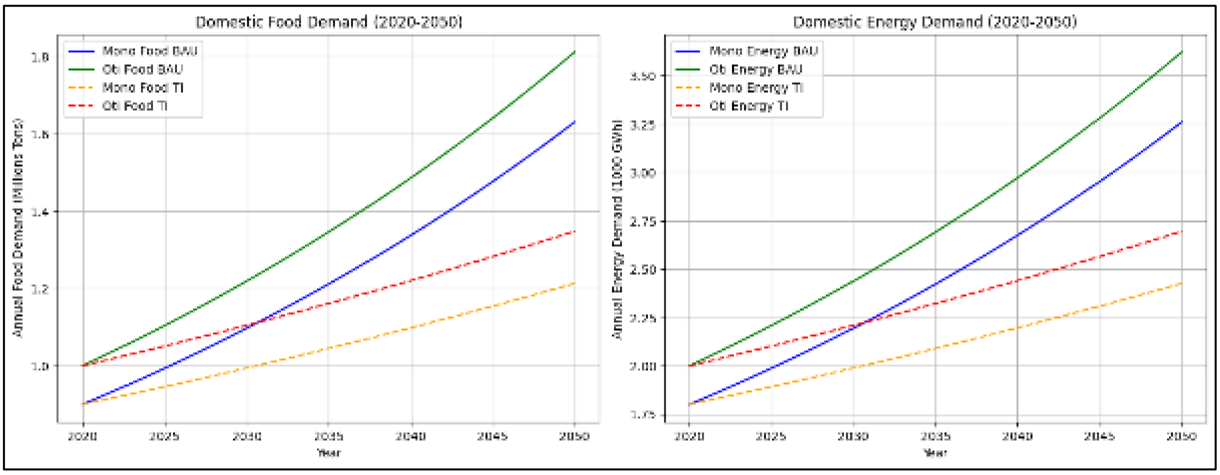

Figure 9 Domestic food and energy demand in Mono and Oti basins under different scenarios

Regarding domestic food demand (left graph), under the BAU scenario, represented by the blue (Mono) and green (Oti) lines, food demand steadily increases, reaching approximately 1.6 million tons for Oti and 1.4 million tons for Mono by 2050. This growth reflects the combined impacts of population growth and the expansion of agricultural land, as highlighted in the Agricultural Analysis Report for the Mono and Oti Basins (UNEP, 2001). In contrast, under the TI scenario, illustrated by the orange (Mono) and red dashed (Oti) lines, a notable reduction in demand is attributed to the introduction of sustainable agricultural practices. These improvements align with the recommendations of the National Plan for Resilient Agriculture (Abegunde et al., 2019), which advocates for modern irrigation techniques and soil management. The stabilization of food demand after 2040 demonstrates the effectiveness of these measures, consistent with the findings of the Agriculture and Food Security Report (Ministry of Agriculture, 2019). Concerning domestic energy demand (right graph), the BAU scenario, represented by the blue (Mono) and green (Oti) lines, shows a sustained increase, reaching approximately 3.5 GWh/year for Oti and 3 GWh/year for Mono by 2050. This trend reflects the growing energy needs driven by economic development and population growth, as noted in the National Energy Report (Togolese Energy Agency, 2021). However, under the TI scenario, represented by the orange (Mono) and red dashed (Oti) lines, significant reductions are observed, thanks to the introduction of hybrid technologies such as hydropower and solar panels. These efforts align with the objectives of the African Energy Transition Program (APTE) for 2063. The effectiveness of these solutions becomes particularly evident after 2040, where energy demand growth stabilizes.

In conclusion, the projections highlight the central role of technological innovations in reducing pressure on food and energy resources in the Mono and Oti basins. For food resources, the adoption of modern irrigation techniques and soil conservation, as outlined in the State of Food Security and Nutrition in the World (SOFI) Report in 2024, is essential. For energy resources, the Sustainable Energy Report for the Mono and Oti Basins emphasizes the importance of increased investments in renewable energy, which are critical to managing future needs and achieving sustainability goals.

3.6. Correlations between environmental and economic variables

The correlation results between the different variables rainfall, flow, energy, and agricultural yield reveals significant relationships that emphasize the interdependence between natural resources and human activities (Fig 10).

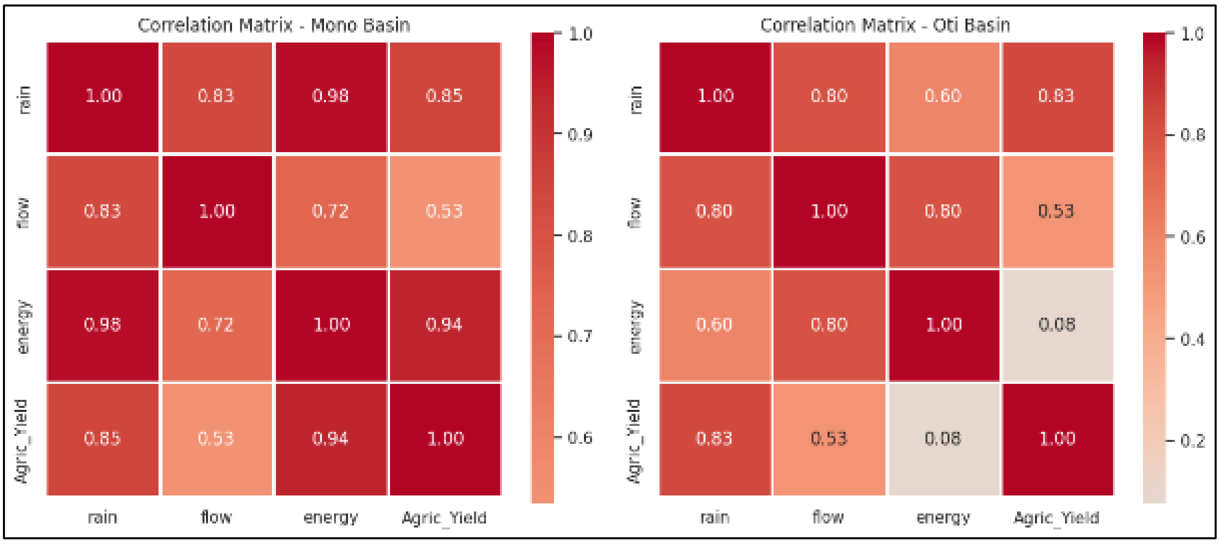

Figure 10 Correlation results between the different variables-rainfall, flow, energy, and agricultural yield

These two correlation matrices illustrate the relationships between key variables rain, flow, energy, and agricultural yield in the Mono Basin (on the left) and the Oti Basin (on the right). The comparison between the two matrices reveals important patterns and differences between the basins. Starting with the Mono Basin, we observe several strong positive correlations. The relationship between rain and energy production stands out with a correlation of 0.98, indicating that rainfall strongly influences energy generation, likely due to the basin's reliance on hydropower. Similarly, rain and flow have a significant correlation (0.83), a logical outcome since more rainfall leads to higher river flow levels. Another critical finding is the high correlation between rain and agricultural yield (0.85), suggesting that rainfall is essential for supporting agricultural productivity in this region. Moreover, the relationship between energy and agricultural yield is also notably strong (0.94), implying that energy availability, perhaps through irrigation or mechanization, plays a vital role in enhancing agricultural output. However, the connection between flow and agricultural yield is weaker (0.53), indicating that while water flow impacts agriculture, other factors such as water management may moderate this relationship. In contrast, the Oti Basin presents a slightly different picture. The correlation between rain and flow remains strong (0.80), reflecting a similar pattern to the Mono Basin, where rainfall directly affects river flow. However, the correlation between rain and energy is lower in the Oti Basin (0.60), suggesting that rainfall has a less direct impact on energy production compared to the Mono Basin. The rain-agricultural yield correlation (0.83), though still high, is comparable to the Mono Basin, emphasizing that rainfall remains a crucial factor for agriculture. Interestingly, the relationship between energy and agricultural yield is strikingly low (0.08), indicating that energy production in the Oti Basin does not significantly affect agricultural output. This difference may reflect variations in energy sources, agricultural practices, or water infrastructure between the two regions. Additionally, the flow-agricultural yield relationship shows a moderate correlation (0.53), indicating that river flow has a more limited impact on agriculture in the Oti Basin, similar to the Mono Basin. Comparing the two basins, the Mono Basin demonstrates stronger overall correlations, particularly between rain, energy, and agricultural yield, suggesting a more interconnected system where water, energy, and food are tightly linked. In contrast, the Oti Basin shows weaker relationships, especially between energy and agricultural yield, highlighting different dynamics in the basin. These variations could be attributed to differences in energy production methods, water management systems, or regional agricultural practices.

3.7. Water-Energy- Food (WEF) Nexus composite indices

AHP is a widely used method for indicator performance evaluation (Russo & Camanho 2015; Nhamo et al. 2020), presumably because it elucidates preference information from the decision makers in a manner which they find easy to understand (Banwet & Deshmukh, 2008). The basic step was undertaken by the pairwise comparison to determine the relationship among WEF nexus components in the study area. It shows AHP helps to formulate and analyze sustainability indicators (Ray & Shaw 2019)

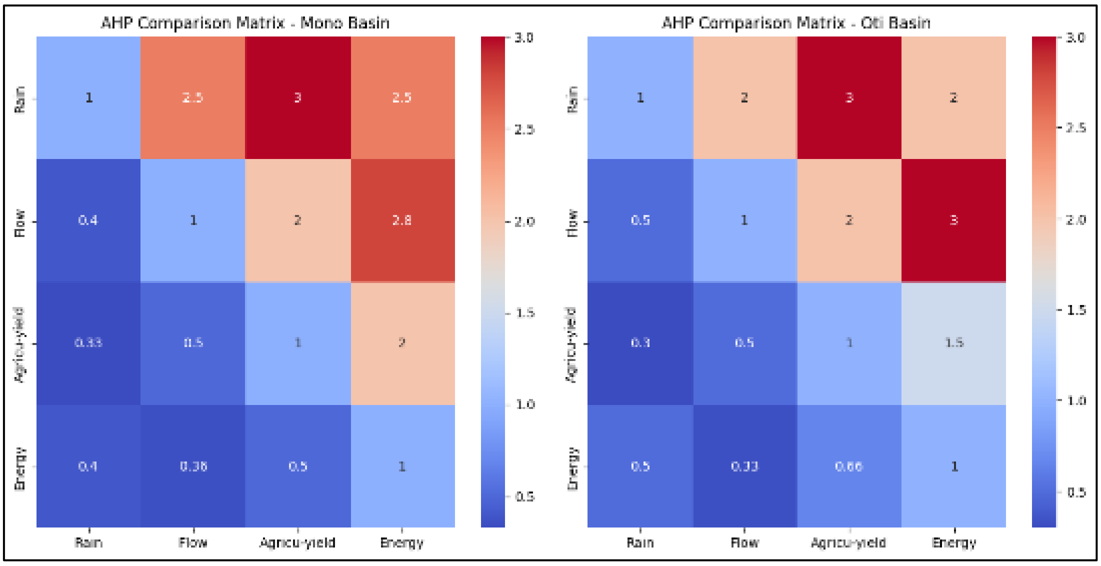

Figure 11 The comparison matrix for AHP

The graph of Fig 11 presents two AHP (Analytic Hierarchy Process) comparison matrices for the Mono and Oti basins, analyzing four key variables-rainfall (Rain), flow (Flow), agricultural yield (Agricu-yield), and energy (Energy) within the context of the Water-Energy-Food (WEF) nexus. In the Mono Basin, rainfall is a dominant factor, directly influencing other sectors, particularly river flow (2.5) and agricultural yield (3.0). This relationship reflects the critical role of abundant rainfall in ensuring sustainable water management and supporting agriculture. River flow plays a moderate yet crucial role, particularly for energy production, with a strong interdependence (2.8), underscoring the region's reliance on consistent water supply for its energy infrastructure. Agricultural yield also shows some dependence on rainfall (0.33) and a moderate influence on river flow (0.5), illustrating how agricultural practices impact water management in this region. Finally, the importance of energy is highlighted, with close links to river flow (0.4) and agricultural practices (0.5), reflecting the need for efficient water management to meet the basin's energy demands.

In contrast, in the Oti Basin, rainfall remains the most influential factor but has an even more pronounced impact on river flow (2.0) and agricultural yield (3.0). This increased importance underscores the region's vulnerability, where water availability largely depends on this single rainy season. River flow, as in the Mono Basin, is essential but plays an even more crucial role in energy production (3.0), highlighting the heightened pressure on water resources in this basin to support energy needs. Agricultural yield is also affected by rainfall, but its connection to energy production (1.5) is weaker than in the Mono Basin, which could indicate a lower integration of agricultural activities into the energy production chain. As for energy, although important, it is primarily influenced by river flow (3.0) in this basin, showing that energy production in the Oti Basin relies even more heavily on a consistent flow for hydroelectric generation.

3.8. Analysis of overall WEF nexus performance in livelihoods

The sensitivity estimation of the Water-Energy-Food (WEF) nexus to livelihoods components provides valuable insights into how changes in these key sectors influence the sustainability and resilience of local communities.

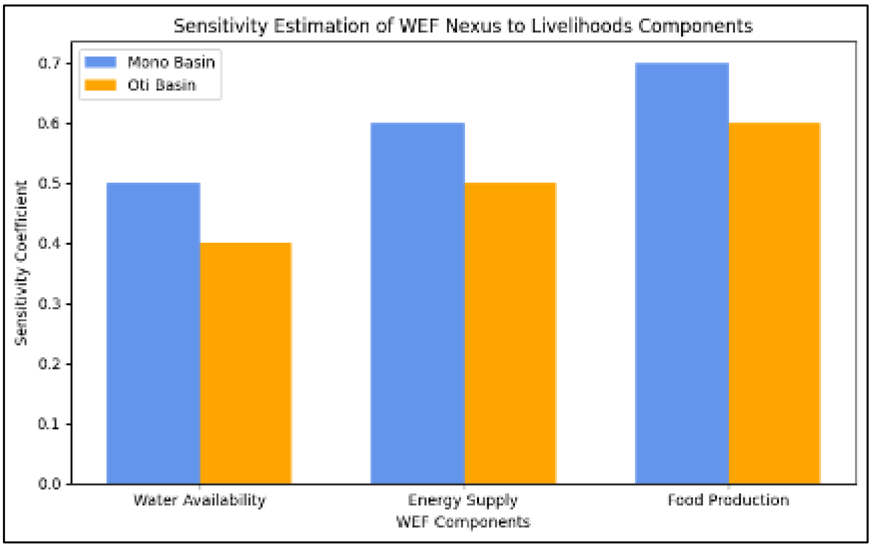

Figure 12 Sensitivity estimation of WEF nexus to livelihoods components

The Fig 12 provides a quantified view of the sensitivity of different livelihood components to the WEF (Water-Energy-Food) nexus resources in the Mono and Oti basins, focusing on water availability, energy supply, and food production. The sensitivity coefficients for each component are represented, with the Mono Basin generally showing higher sensitivity than the Oti Basin. In terms of water availability, the Mono Basin shows a higher sensitivity (~0.5) compared to the Oti Basin (~0.4), indicating a greater impact on livelihoods in Mono. Energy supply also exhibits a stronger influence in the Mono Basin (~0.65) versus the Oti Basin (~0.45), suggesting that energy plays a more critical role in sustaining livelihoods in Mono. Food production, the most influential factor in both basins, is slightly more important in the Mono Basin (~0.7) compared to the Oti Basin (~0.6). Overall, the Mono Basin demonstrates higher sensitivity across all LWEF components, with food production being the most sensitive in both basins, particularly in the Mono Basin. This suggests a greater need for resource management and policy focus in the Mono Basin to support livelihoods.

3.9. Evaluating the Sustainability of the WEF Nexus Over Time

To evaluate sustainability, a sustainability index SWEF was calculated by combining economic, environmental, and social factors. The weighting coefficients were adjusted based on local priorities and future projections, and this index is calculated at regular intervals to monitor sustainability trends over time. The graph (Fig 13) illustrates the evolution of the Water-Energy-Food (WEF) nexus sustainability index for both the Mono and Oti basins from 2020 to 2050, measuring how well these interconnected sectors are managed to ensure long-term sustainability. The sustainability index for the Mono Basin remains relatively stable, oscillating between 0.7 and 0.85, consistently higher than that of the Oti Basin. Despite some fluctuations, this indicates a more effective management of water, energy, and food resources in the Mono Basin, which demonstrates greater resilience and sustainability. This sustained higher index suggests stronger policies or environmental conditions supporting the WEF nexus in the Mono Basin. On the other hand, the Oti Basin has a generally lower index, ranging between 0.6 and 0.7, with more pronounced variability, particularly in the early years (2020-2030). This indicates that the Oti Basin faces greater challenges in maintaining sustainability, potentially due to factors like weaker infrastructure, policy gaps, or environmental pressures. However, the global comparison between the basins shows that while the Mono Basin consistently outperforms the Oti Basin, both indices tend to stabilize from 2030 onwards, suggesting improved resource management practices or external support in both basins. The Oti Basin, despite starting lower, shows signs of gradual improvement, indicating that with appropriate interventions, the sustainability gap between the two basins could narrow over time. In summary, while both basins face challenges, the Mono Basin demonstrates stronger long-term sustainability, with the Oti Basin slowly catching up, highlighting the need for targeted policy measures and better resource management in the latter.

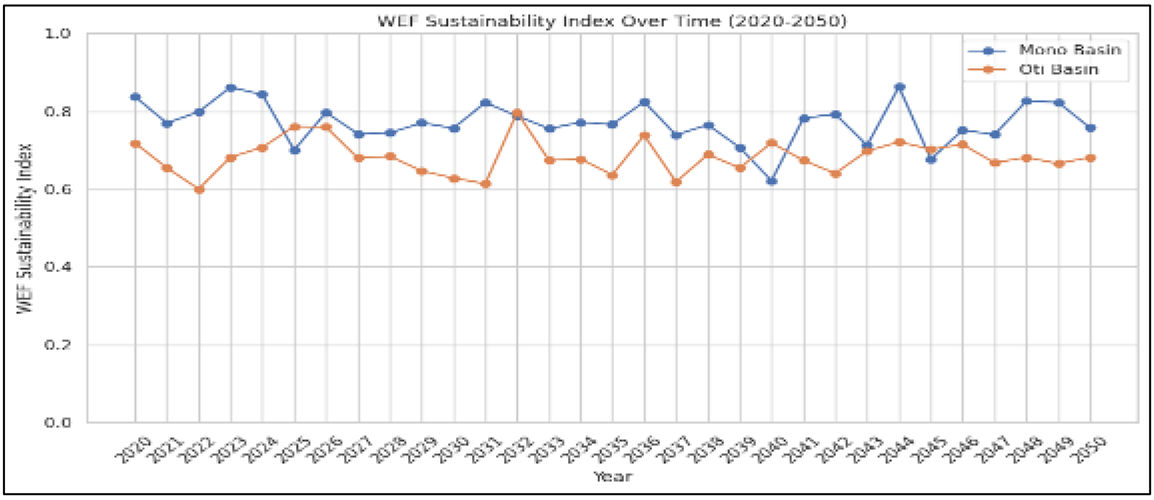

Figure 13 Sustainability Index

4. Discussion

The findings from this study build a coherent narrative, linking the interplay of environmental and economic variables with resource demands and management strategies. By exploring water intensity and energy vulnerability through scenario analysis, the study underscores the critical role of technological advancements in enhancing sustainability, aligning with conclusions by Nhamo et al. (2020) on the necessity of innovative approaches in resource efficiency. Moreover, the projections of future resource demands and their correlations with environmental factors emphasize the urgency of adopting cross-sectoral policies to mitigate risks, as suggested by the FAO (2019) and Akpoti et al. (2021) in similar contexts. The use of composite indices, as supported by Banwet & Deshmukh (2008), and sensitivity analysis provides actionable insights, enabling decision-makers to prioritize interventions that strengthen resilience and sustainability. Collectively, these results integrate diverse aspects of resource dynamics, offering a comprehensive framework for addressing the challenges of climate variability and growing resource demands in the Mono and Oti basins, consistent with frameworks proposed by Russo & Camanho (2015).

The study has present limitations: First, it relies on available data on climate variability and resource demands, which may be incomplete or subject to uncertainties. While the future projections are relevant, they are prone to potential errors related to data quality and coverage. Second, the scenarios used for sensitivity analysis and composite index modeling assume linear or constant relationships between variables, which may not capture the full complexity of environmental and socio-economic interactions. Third, the study focuses on regional analyses but may overlook local dynamics specific to communities or resource management practices in the Mono and Oti basins. Additionally, although cross-sectoral policies are recommended, their implementation may face institutional and political challenges, as well as divergent interests among sectors. Finally, while the importance of technological advancements is theoretically validated, the accessibility and practical application of these technologies in local contexts may pose challenges, particularly in terms of financing and technical capacities.

To improve the study's outcomes, several areas need to be addressed: Expanding scenarios to include diverse climatic and socio-economic trajectories would better account for future uncertainty and associated risks. Considering a broader range of adaptation and resource management scenarios would be beneficial. Strengthening local capacities through programs for water resource managers and local decision-makers is necessary to integrate study results into local policies on natural resource management and climate resilience. Rigorous monitoring and evaluation mechanisms should be established to assess the effectiveness of adopted cross-sectoral policies, particularly those aimed at enhancing community resilience to climate change. Increasing interdisciplinary collaboration among researchers, governments, NGOs, and local communities will ensure that proposed interventions are appropriate and feasible, addressing the economic, environmental, and social dimensions of the basins. Finally, fostering technological innovation for sustainable resource management, including smart water monitoring systems, renewable energy management, and resource efficiency optimization, is essential. Partnerships with tech companies could play a key role in implementing large-scale solutions.

5. Conclusion

In conclusion, this study offers a comprehensive analysis of the interconnections between environmental and economic variables, with a particular focus on the Water-Energy-Food (WEF) Nexus in the Mono and Oti basins. By characterizing water intensity for food production and energy generation through scenario analysis, the study highlights the vulnerabilities of water and energy systems, offering valuable projections of future demands. Understanding domestic water, food, and energy demand projections under different scenarios is essential for developing informed water management strategies, especially considering the potential impacts of climate change and technological advancements.

The study emphasizes the significant correlations between environmental variables such as rainfall, flow, energy, and agricultural yield, underscoring the interconnectedness of natural resources and human activities. The application of composite indices and sensitivity analysis for the WEF nexus provides actionable insights into how these sectors influence the livelihoods and sustainability of local communities. Furthermore, the sustainability index (SWEF) calculated in this study integrates economic, environmental, and social dimensions, offering a holistic approach to evaluating long-term resource management.

Overall, the findings of this study not only contribute to a better understanding of resource dynamics in the Mono and Oti basins but also provide a strategic framework for policymakers and stakeholders to address future challenges in water, energy, and food security, fostering sustainability and resilience in the face of climate change.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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