

Global Warming and the Water-Energy-Food Nexus: Insights from Geo-Information and Earth Observation

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Dates:

Received: 08/01/2025

Accepted: 31/07/2025

Published: 12/11/2025

Citation:

Alonge, O. O. (2025).
Global Warming and the
Water-Energy-Food
Nexus: Insights from Geo-
Information and Earth
Observation. *Nigerian
Journal of Sustainability
Research*, 3(2), 4-15.
[https://njsr.com.ng/index.
php/home/article/view/45](https://njsr.com.ng/index.php/home/article/view/45)

Abstract

Global warming, driven by anthropogenic greenhouse gas emissions, is a major threat to the sustainability of water, energy, and food (WEF) systems. These systems are deeply interconnected, and disruptions in one domain can cascade across the others, particularly in vulnerable regions. This article explores the multifaceted impacts of global warming on the WEF nexus, emphasizing the role of geoinformation science and Earth Observation technologies in monitoring and mitigating these effects. Drawing on comparative insights from Nigeria and India—two populous, climate-sensitive developing countries—the study highlights how climate-induced changes in precipitation, temperature, and extreme weather events compromise agricultural productivity, energy infrastructure, and water availability. The paper also examines the trade-offs and synergies inherent in WEF resource management, advocating for integrated, data-driven approaches to enhance resilience. By leveraging remote sensing, GIS, and satellite-based monitoring tools, stakeholders can gain a deeper understanding of spatial-temporal dynamics and inform more effective, sustainable policy interventions. The findings underscore the urgency of interdisciplinary strategies to address climate vulnerabilities and support the achievement of Sustainable Development Goals (SDGs) 2, 6, 7, and 13.

Keywords

Global Warming, Water-Energy-Food Nexus, Climate Change, Earth Observation, GIS, Sustainable Development

1. Introduction

The accelerating pace of global warming presents one of the most pressing challenges of the 21st century. Scientific

consensus affirms that rising global temperatures—primarily caused by anthropogenic emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxide—are intensifying climate variability and increasing the frequency of extreme weather events (Pörtner et al., 2022; WMO, 2022). These climatic shifts have profound implications for the water-energy-food (WEF) nexus, a conceptual framework that captures the interdependencies among essential resources required for human survival and environmental sustainability.

The WEF nexus is particularly vulnerable to the impacts of climate change. Water availability is affected by altered precipitation patterns and increased evapotranspiration; energy systems are strained by temperature extremes and infrastructure damage; and food production is jeopardized by droughts, floods, and shifts in agroecological zones. These disruptions are not isolated but interconnected, often compounding one another in complex feedback loops. Understanding and managing these interactions is critical to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

This article examines the impact of global warming on the WEF nexus from the perspective of geo-information science and Earth Observation (EO). These technologies offer powerful tools for monitoring environmental changes, assessing vulnerabilities, and informing adaptive strategies. Drawing on case studies from Nigeria and India, this paper examines how climate change manifests in diverse socio-political and ecological contexts, and how Earth Observation (EO) and Geographic Information Systems (GIS) can facilitate integrated, sustainable resource management. The study aims to contribute to the growing body of interdisciplinary research that seeks to operationalize the WEF nexus in the face of global climate change.

2. Literature Review

2.1 Climate Change and the WEF Nexus

The water-energy-food (WEF) nexus has become a central framework for understanding the interconnectedness of essential resources in the context of global environmental change. As global warming intensifies, the stability and sustainability of WEF systems are increasingly threatened by climate-induced disruptions such as altered precipitation patterns, rising temperatures, and extreme weather events.

Climate change poses significant challenges to the Water-Energy-Food (WEF) nexus in developing countries, where environmental stressors and socio-economic pressures converge to intensify resource scarcity and vulnerability. Regions such as South Asia and the Middle East and North Africa (MENA) are particularly affected, experiencing heightened water stress, agricultural disruption, and energy insecurity (Rasul & Sharma, 2015; "Towards

COP27: The Water-Food-Energy Nexus in a Changing Climate in the Middle East and North Africa", 2023). Vulnerable populations bear the brunt of these impacts, as disrupted supply chains and limited adaptive capacity exacerbate food and energy insecurity (Behnassi, 2019). Despite the growing recognition of the WEF nexus, governance structures often remain fragmented, lacking the integrated frameworks needed to address these interdependencies effectively (Sukhwani & Shaw, 2022; Dlamini et al., 2024). A multidisciplinary, nexus-based approach can enhance policy coherence and resource efficiency, supporting more resilient adaptation strategies (Rasul & Sharma, 2015; Dlamini et al., 2024). However, critics caution that overly centralized nexus models may overlook localized, context-specific solutions that are crucial for sustainable development in diverse socio-economic settings.

The integrated management of the Water-Energy-Food (WEF) Nexus offers a strategic framework for enhancing global food security under climate change pressures. By acknowledging the interdependencies among water, energy, and food systems, this approach enables synergistic resource management that reduces inefficiencies and environmental impacts (Swatuk & Cash, 2018; Albatayneh, 2023). Integrated governance models not only support climate adaptation through improved resilience and resource optimization—such as precision agriculture and efficient irrigation—but also bolster food production in uncertain environmental conditions (Sukhwani & Shaw, 2022; Kanwar et al., 2021). Effective implementation hinges on collaborative, multi-level governance and regional cooperation, particularly in climate-vulnerable regions, to ensure equitable and sustainable outcomes (Lalawmpuii & Rai, 2023; Albatayneh, 2023). However, persistent challenges, such as sectoral fragmentation and unequal access to resources, highlight the need for continued innovation and inclusive policy development.

Gao et al. (2024) conducted a comprehensive review of methodologies used to assess climate change impacts on the WEF nexus, categorizing them into four main approaches: physics-based modelling, statistical methods, supervised learning, and operational optimization. Their findings highlight the dominance of hydrological and interdisciplinary models, especially at regional scales, and emphasize the need for improved spatial resolution and the integration of artificial intelligence to address uncertainties and extreme climate events.

An editorial by Gaetani et al. (2023) highlights the increasing pressure on WEF systems resulting from population growth, urbanization, and technological advancements, all of which are exacerbated by climate variability. The authors argue that poorly coordinated policy actions can degrade ecosystems and intensify resource competition, making integrated governance essential.

2.2 Regional Perspectives: Nigeria and India

Implementing the Water-Energy-Food (WEF) nexus in developing countries such as Nigeria and India reveals a complex landscape of interlinked challenges. Rapid population growth in both nations is placing immense pressure on already strained water, energy, and food

systems, demanding integrated strategies to manage competing demands (Hira, 2025). Climate change further exacerbates these pressures. India is grappling with shifting rainfall patterns and rising temperatures that threaten agricultural productivity, while Nigeria faces recurring droughts and floods that disrupt both farming and energy generation (Barik et al., 2017). These environmental stressors underscore the urgency of adopting adaptive, cross-sectoral approaches to resource management.

Governance and institutional coordination remain significant hurdles in both contexts. In India, fragmented sectoral policies often fail to reflect the interconnected nature of water, energy, and food systems, leading to inefficiencies and missed opportunities for synergy (Rasul & Neupane, 2021). Nigeria, meanwhile, struggles with weak institutional frameworks and limited cross-sector collaboration, further complicated by socio-political instability and poverty. These systemic issues are compounded by financial and technological constraints that limit access to sustainable solutions such as renewable energy and efficient irrigation systems (Chakraborti et al., 2024). Moreover, Elum et al. (2017) highlight the gendered dimensions of climate vulnerability in Nigeria, where women disproportionately bear the burden of water and food insecurity, particularly in rural communities with limited infrastructure and access to climate-resilient technologies.

Despite these challenges, both countries are exploring promising pathways. In India, rapid industrialization and urban expansion have intensified groundwater depletion, prompting calls for integrated groundwater governance under the WEF nexus framework (Mukherji, 2022). Shah et al. (2023) note that India is making strides in aligning its water, energy, food, and environmental policies, though institutional gaps remain. Nigeria, too, has opportunities to adopt circular economy principles and invest in renewable energy to reduce dependence on fossil fuels and enhance resource efficiency (Verma et al., 2024). Inclusive governance and stakeholder engagement, like participatory models that involve local communities, are essential to ensure that WEF nexus strategies are both effective and equitable (Karutz et al., 2022).

2.3 Role of Geo-Information and Earth Observation

Geo-information science and Earth Observation (EO) technologies are increasingly recognized as essential tools for monitoring and managing the Water-Energy-Food (WEF) nexus, particularly under the pressures of climate change. Remote sensing platforms such as MODIS, Landsat, and Sentinel provide high-resolution, real-time data on land use, vegetation health, surface temperature, and water bodies, enabling dynamic assessments of environmental change. These capabilities are particularly valuable in developing countries like Nigeria and India, where rapid urbanization and population growth are intensifying resource stress. O'Connor et al. (2020) emphasize EO's contribution to tracking progress toward the Sustainable Development Goals (SDGs), especially in relation to water availability, agricultural productivity, and energy infrastructure.

In practical terms, EO data has been instrumental in identifying climate risk hotspots and informing targeted interventions through GIS-based vulnerability mapping. In Nigeria, EO tools have supported the monitoring of water stress and environmental degradation in sensitive regions like the Niger Delta, where oil pollution and water scarcity intersect (Sivakumar, 2021). In India, EO data has been used to assess river basin health and guide water allocation strategies, particularly in agriculture-dependent regions (Lalawmpui & Rai, 2023). For energy systems, EO data supports the siting of renewable energy infrastructure by analyzing solar radiation and wind patterns (Li & Zhang, 2023), while also helping to monitor water use in thermal power plants, a key concern in India's energy sector (Senzanje et al., 2022).

Despite these advances, the full potential of EO technologies remains underutilized in policy and planning. Gao et al. (2024) argue that greater integration of EO data into decision-making frameworks is needed, along with improved interoperability among datasets and the development of user-friendly platforms for diverse stakeholders. In agriculture, EO applications have proven effective in monitoring crop health, soil moisture, and land use changes, enhancing food security through more efficient resource use (Guerra et al., 2021). Early warning systems based on EO data are particularly valuable in India's monsoon-dependent farming systems (Caceres et al., 2020), while in Nigeria, they support efforts to combat soil degradation and improve productivity. Ultimately, EO data offers a powerful means of strengthening WEF governance and aligning national strategies with sustainable development goals (Bai and Sarkis, 2022), but realizing this potential requires addressing persistent challenges in data access, institutional capacity, and stakeholder engagement.

3. Methodology

This study adopts a qualitative, interdisciplinary desktop research approach to investigate the impacts of global warming on the Water-Energy-Food (WEF) nexus, with a particular emphasis on the role of geoinformation science and Earth Observation (EO) technologies. The methodology integrates a comparative case study design with a systematic thematic literature review to explore how EO tools are conceptualised and applied in WEF-related research and policy, particularly in the contexts of Nigeria and India.

3.1 Research Design

The research is structured around two core components:

Comparative Case Study Analysis

Nigeria and India were selected as comparative case studies due to their shared characteristics as climate-vulnerable, rapidly developing countries with large populations and significant reliance on agriculture and fossil fuels. These countries also face similar challenges in water scarcity, energy access, and food insecurity. However, they differ in governance structures,

technological adoption, and socio-economic conditions, offering a rich basis for comparative insights. The case study approach enables a contextualized understanding of how EO technologies are integrated into national WEF strategies and climate adaptation efforts.

Thematic Literature Review

A systematic review of peer-reviewed literature published between 2020 and 2025 was conducted to identify key trends, challenges, and innovations in the application of EO technologies within the WEF nexus under climate stress. The review focused on literature from databases like Scopus, Web of Science, and Google Scholar. Search terms included combinations of “WEF nexus,” “climate change,” “Earth observation,” “remote sensing,” “GIS,” “sustainable development,” and “developing countries.” Grey literature from international organizations (e.g., FAO, UNEP, World Bank) and national policy documents were also included to capture practical and policy-oriented perspectives.

3.2 Data Sources

The study relies exclusively on secondary data, including:

Scientific Literature: Peer-reviewed journal articles, conference proceedings, and technical reports relevant to EO applications in WEF systems.

Climate and Environmental Reports: Including the IPCC Sixth Assessment Report (2022), WMO State of the Global Climate (2022), and national climate adaptation strategies from Nigeria and India.

Socio-economic and Development Data: Sourced from the FAO, World Bank, and national statistical agencies, covering indicators such as food security, energy access, water availability, and population growth.

Policy and Institutional Documents: National development plans, EO strategy documents, and WEF-related policy frameworks from both countries.

3.3 Analytical Framework

The analysis is guided by the WEF nexus framework, which emphasizes the interdependencies, trade-offs, and synergies among water, energy, and food systems. This framework is applied to:

- Examine the direct and indirect impacts of global warming on each component of the nexus.
- Identify systemic feedback loops and cascading effects across sectors.
- Evaluate how EO technologies are positioned within national and international strategies for climate adaptation and sustainable development.

- Compare the institutional, technological, and policy contexts that shape the adoption and effectiveness of EO tools in Nigeria and India.

This approach allows for a nuanced understanding of how EO technologies contribute to integrated resource management and climate resilience, while also highlighting the barriers and opportunities specific to each national context.

4. Results and Discussion

4.1 Impacts of Global Warming on the WEF Nexus

Global warming has profound and multifaceted effects on the water-energy-food (WEF) nexus. These impacts are not isolated but interconnected, often resulting in cascading consequences across sectors. The analysis reveals that climate-induced disruptions, such as altered precipitation patterns, rising temperatures, and extreme weather events, undermine the stability and sustainability of WEF systems.

Water Sector

Changes in precipitation and increased evapotranspiration due to global warming have led to reduced water availability and quality. In many regions, including sub-Saharan Africa and South Asia, prolonged droughts and erratic rainfall patterns have diminished surface and groundwater resources (Hamidov et al., 2022). This directly affects both agricultural irrigation and hydropower generation, creating a feedback loop that exacerbates food and energy insecurity.

Energy Sector

The energy sector is affected through both supply and infrastructure vulnerabilities. Hydropower, which depends on consistent water flow, is particularly sensitive to climate variability. In East Africa, Sridharan et al. (2019) found that reduced river discharge due to warming trends significantly decreased electricity generation capacity. Additionally, thermal power plants experience reduced efficiency at higher ambient temperatures, while extreme weather events such as floods and storms damage energy infrastructure (Mpandeli et al., 2018).

Food Sector

Agricultural systems are highly climate-sensitive. Rising temperatures and shifting precipitation patterns reduce crop yields, increase pest and disease outbreaks, and shorten growing seasons. Mabhaudhi et al. (2019) emphasized that smallholder farmers in Southern Africa are especially vulnerable due to limited access to adaptive technologies. Moreover, the competition for water between agriculture and energy production intensifies under climate stress, further threatening food security.

4.2 Trade-offs and Synergies in the WEF Nexus

The interdependence of WEF systems means that interventions in one domain can have unintended consequences in others. For example, the promotion of biofuels as a renewable energy source can reduce fossil fuel dependence but may also divert water and land from food production, exacerbating food insecurity (Lina et al., 2021; Ashwin and Prachi, 2022). Increasing irrigation boosted food production but reduced hydropower, and wind energy expansion reduced greenhouse gas (GHG) emissions and water demand while enhancing electricity supply (Lina et al., 2021). Conversely, integrated resource planning can yield synergies, such as using treated wastewater for irrigation or deploying solar-powered irrigation systems, that enhance sustainability across sectors.

4.3 Comparative Insights: Nigeria and India

The comparative analysis of Nigeria and India illustrates how socio-political and environmental contexts mediate the impacts of global warming on the WEF nexus.

- Nigeria faces challenges such as political instability, conflict between farmers and herders, and weak infrastructure. These factors hinder effective resource governance and exacerbate climate vulnerabilities (Okereke et al., 2018; Elum et al., 2017).

- India, while more technologically advanced, grapples with rapid urbanization, industrialization, and groundwater depletion. Mukherji (2022) notes that India's energy-intensive agricultural practices and fragmented water governance structures limit its adaptive capacity.

Despite these differences, both countries demonstrate the urgent need for integrated, climate-resilient WEF strategies.

4.4 Role of Geo-Information and Earth Observation

Geo-information science and Earth Observation (EO) technologies play a pivotal role in understanding and managing the WEF nexus under climate stress. Remote sensing tools such as MODIS and Sentinel-2 provide critical data on land surface temperature, vegetation health, and water bodies. GIS enables spatial analysis of vulnerability and resource distribution, supporting evidence-based decision-making.

O'Connor et al. (2020) emphasize that EO contributes to monitoring progress toward the SDGs by providing timely, high-resolution data. However, Gao et al. (2024) caution that EO tools are often underutilized in policy frameworks. Bridging this gap requires capacity-building, data integration, and stakeholder engagement to translate geospatial insights into actionable strategies.

5. Conclusion and Recommendations

5.1 Conclusion

The accelerating impacts of global warming on the water-energy-food (WEF) nexus present a formidable challenge to sustainable development, particularly in climate-vulnerable regions such as Nigeria and India. This study has demonstrated how rising temperatures, shifting precipitation patterns, and extreme weather events disrupt the availability and interdependence of water, energy, and food systems. These disruptions are not only environmental but also socio-political, as they intersect with governance, infrastructure, and socio-economic inequalities.

The comparative analysis of Nigeria and India reveals that while both countries face similar climate-induced pressures, their responses are shaped by distinct institutional capacities and development trajectories. In both contexts, the integration of geo-information science and Earth Observation (EO) technologies offers a promising pathway for monitoring environmental change, identifying vulnerabilities, and informing adaptive strategies.

However, the full potential of EO and GIS remains underutilized in policy and planning. Bridging this gap requires not only technological investment but also institutional coordination, capacity building, and inclusive governance frameworks that prioritize resilience and equity.

5.2 Recommendations

To enhance the resilience of the WEF nexus under climate change, the following recommendations are proposed:

1. Promote Integrated Nexus Governance

Encourage cross-sectoral coordination among water, energy, and agricultural ministries to align policies and avoid conflicting resource use.

2. Invest in Geo-Spatial Infrastructure

Expand access to EO and GIS tools, particularly in low- and middle-income countries, to support real-time monitoring and early warning systems.

3. Strengthen Data Integration and Accessibility

Develop interoperable platforms that combine EO data with socio-economic indicators to support evidence-based decision-making.

4. Support Climate-Resilient Technologies

Promote the adoption of sustainable agricultural practices, renewable energy systems, and water-saving technologies that reduce vulnerability to climate shocks.

5. Enhance Capacity-Building and Education

Train local stakeholders, including policymakers, researchers, and community leaders, in the use of EO and GIS for climate adaptation and resource management.

6. Foster International Collaboration

Encourage knowledge exchange and joint research initiatives across countries and regions to share best practices and innovations in WEF nexus management.

By adopting these strategies, governments, researchers, and development partners can work toward a more resilient and sustainable future in the face of global climate change.

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