The Water-Energy-Food Nexus in Madagascar: Interdependencies, Cascading Failures, and an Integrated Governance Framework

Rovatiana Salema ANDRIANASOLOMAHEFA

Faculty of Public Governance and International Studies, Doctoral School of Public Administration, National University of Public Service, Budapest, Hungary (email: andrianasolomahefa.rovatiana.salema@stud.uni-nke.hu; rovatiana.salena@gmail.com)

DOI: 10.59258/hk.24124

Abstract

Madagascar's concurrent crises of energy poverty (33.7% electrification), acute food insecurity (1.63 million people in Integrated Food Security Phase Classification (IPC) Phase 3+ in 2024), and watershed degradation (4.85 million hectares of forest lost since 2000) are structurally interdependent, yet are governed in institutional silos with no cross-sectoral coordination mechanism. This paper maps the Water-Energy-Food (WEF) nexus dynamics of Madagascar, tests the hypothesis that institutional fragmentation – not physical resource scarcity – is the binding constraint on nexus performance, and proposes an evidence-based integrated governance framework. A sequential mixed-methods design integrates systematic secondary data synthesis with qualitative institutional analysis following a governance audit framework and the FAO three-systems nexus model. Five quantified nexus feedback loops are identified, the most critical being a biomass-deforestation-hydropower cascade that simultaneously impairs energy supply, watershed function, and food system productivity. Despite the per capita renewable freshwater endowments of ~12,000 m³/year due to climatic heterogeneity, this resource is distributed unevenly across the country; while this is double the Sub-Saharan African average, only 14% of the population accesses safely managed water, and 85% of primary energy derives from biomass. A 96% agricultural water withdrawal share, 47% child stunting rate, and projected temperature increases of 3–5 °C by 2100 compound these structural deficits. Madagascar's nexus failures are governance failures. To address the identified governance and resource management challenges, this study proposes three high-leverage policy measures. First, establish a National Water-Energy-Food (WEF) Nexus Coordination Secretariat to strengthen a cross-sectorial coordination and policy coherence. Second, implement nexus-aware investment screening anchored in the 2024 ECA-WFP geospatial initiative to ensure that public and private investments account for WEF interdependencies. Third, expand off-grid renewable energy, like solar deployment linked to productive agricultural use requirements, to improve energy access while enhancing agricultural productivity and water-use efficiency.

Keywords

Water-Energy-Food (WEF) Nexus, Madagascar, Food Security, Governance, Hydropower, Sustainable Development.

A víz-energia-élelmiszer összefüggés Madagaszkáron: Kölcsönös függőségek, kaszkádszerű kudarcok és egy integrált irányítási keretrendszer

Kivonat

Madagaszkár egyidejű válságai, mint például az energiaszegénység (33,7%-os villamosítás), az akut élelmiszer-bizonytalanság (1,63 millió ember az Integrált Élelmiszerbiztonsági Fázisbesorolás (IPC) 3+ fázisába került 2024-ben) és a vízgyűjtők degradációja (4,85 millió hektár erdő veszett el 2000 óta) strukturálisan egymástól függenek, mégis intézményi silókban, ágazatközi koordinációs mechanizmus nélkül irányítják őket. Ez a tanulmány feltérképezi Madagaszkár víz-energia-élelmiszer (WEF) nexus dinamikáját, teszteli azt a hipotézist, hogy az intézményi fragmentáció – nem a fizikai erőforrások szűkössége – korlátozza a nexus teljesítményét, majd bizonyítékokon alapuló integrált irányítási keretet javasol. A szekvenciális vegyes módszerű tervezés integrálja a szisztematikus másodlagos adatszintézist a kvalitatív intézményi elemzéssel, egy irányítási audit keretrendszert és a FAO háromosztatú nexus modelljét követve. Öt számszerűsített nexus visszacsatolási hurkot azonosít, amelyek közül a legkritikusabb a biomassza-erdőirtás-vízenergia kaszkád, amely egyszerre rontja az energiaellátást, a vízgyűjtő működését és az élelmiszerrendszer termelékenységét. Annak ellenére, hogy az egy főre jutó megújuló édesvízkészlet ~12 000 m³/év – ami a szubszaharai afrikai átlag kétszerese –, a lakosságnak csak 14%-a fér hozzá biztonságosan kezelt vízhez, és az elsődleges energia 85%-a biomasszából származik. A mezőgazdasági vízkivétel 96%-os aránya, a gyermekkori fejlődés elmaradásának 47%-os, valamint a 2100-ra előrejelzett 3–5 °C-os hőmérséklet-emelkedés súlyosbítja ezeket a strukturális hiányosságokat. Madagaszkár nexus hibái kormányzási hibák. Először is létre kell hozni egy Nemzeti Víz–Energia–Élelmiszer (WEF) Összefüggés-koordinációs Titkárságot a szektorok közötti koordináció és a politikai koherencia erősítése érdekében. Másodszor, a 2024-es ECA–WFP térinformatikai kezdeményezésen alapuló, a nexust figyelembe vevő beruházásszűrést kell bevezetni annak biztosítására, hogy az állami és magánberuházások figyelembe vegyék a víz, az energia és az élelmiszer közötti kölcsönös függőségeket. Harmadszor, ki kell bővíteni a hálózaton kívüli megújuló energiaforrások, például a napenergia felhasználását, összekapcsolva azt a termelői mezőgazdasági igényekkel, az energiaellátás javítása mellett a mezőgazdasági termelékenység és a vízfelhasználás hatékonyságának növelése érdekében.

Kulcsszavak

Víz-Energia-Élelmiszer (WEF) nexus, Madagaszkár, élelmiszerbiztonság, irányítás, vízenergia, fenntartható fejlődés.

INTRODUCTION

Madagascar presents a paradox that challenges conventional resource-scarcity narratives: it possesses extraordinary natural capital–337 billion m³ of renewable freshwater, 7,800 MW of unexploited hydropower potential, and solar irradiation averaging 5.5 kWh/m²/day–yet consistently records among the worst water, energy, and food security outcomes globally. As of 2024, only 33.7% of Malagasy citizens had access to electricity (*World Bank 2023*); 1.63 million people faced IPC Phase 3 or worse food insecurity conditions (*IPC 2024*); and 4.85 million hectares of forest cover had been lost since 2000, releasing an estimated 2.52 $GtCO_2e$ (*Andriamparany et al. 2023*). This configuration – abundant resources, catastrophic outcomes – is the defining problem that motivates the present analysis.

These aggregate figures, however, obscure a spatial asymmetry that is analytically decisive for the Water-Energy-Food (WEF) nexus. Madagascar's orographic structure concentrates the large majority of annual precipitation on the steep eastern escarpment (*Figure 1*), where short, high-gradient rivers discharge into the Indian Ocean before any significant water capture is possible. The same eastern corridor that generates the 7 800 MW hydropower potential –the energy pillar of the nexus – is thus hydrologically decoupled from the arid south and west, where food insecurity is most acute and where annual rainfall can fall below 400 mm. The result is that the three nexus dimensions are not merely underperforming in parallel: they are spatially misaligned at the outset, so that expanding hydropower on eastern rivers does not automatically relieve water or food stress in the regions that need it most. Understanding this structural disconnection is a precondition for interpreting both the governance failures and the policy interventions analysed in the sections that follow.

Existing research on Madagascar's development challenges addresses these sectors largely in isolation. Agricultural studies focus on productivity constraints (*Minten and Barrett, 2008*); energy studies address electrification gaps (*Nematchoua 2020*); climate studies examine adaptive behavior among smallholder farmers (*Barrett et al. 2025, Davies et al. 2024*). The Water-Energy-Food (WEF) nexus, as applied by *Nkiaka et al. (2023)* across 54 African nations using the WEF Nexus Index, demonstrates that suboptimal performance in all three dimensions simultaneously is the norm in Sub-Saharan Africa, and that the dominant constraint is institutional rather than physical. Yet Madagascar receives no country-specific nexus treatment in this or any comparable analysis. This is the research gap this paper addresses.

The underperformance of Madagascar's WEF nexus is primarily attributable to institutional fragmentation and governance failures, not to physical resource scarcity, and an integrated cross-sectoral governance framework would produce measurably superior outcomes across all three nexus dimensions.

This hypothesis raises the following four interrelated Research Questions (RQ):

- RQ1: What is the current state of Madagascar's water, energy, and food systems relative to regional benchmarks, and where do the most acute deficits lie?
- RQ2: What are the principal WEF nexus feedback mechanisms, what are their quantified magnitudes, and which feedback loops are most damaging?
- RQ3: How does observed and projected climate change modulate the nexus interdependencies, and which pathways are most critical for policy attention?
- RQ4: What governance architecture would most effectively address Madagascar's identified nexus failure modes, and what evidence-based institutional reforms are recommended?

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

The WEF nexus concept, introduced by *Hoff (2011)* at the Bonn 2011 Conference, posits that water, energy, and food are governed as separate systems despite exhibiting deep physical interdependencies. Food and Agriculture Organization of the United Nations (*FAO 2014*) elaborated this insight into a three-pillar planning model emphasizing resource trade-offs and co-management synergies. *Bizikova et al. (2013)* extended this into a practical investment risk framework showing that siloed sectoral investments regularly generate negative externalities across nexus boundaries.

Leck et al. (2015) identified a translation deficit between nexus theory and actionable governance: the framework diagnoses interdependencies well but rarely produces institutional prescriptions. *Rasul (2016)* addressed this in a South Asian context, demonstrating that nexus performance is mediated by trade regimes, fiscal architecture, and institutional coordination capacity. *Herrera-Franco et al. (2024)*, in a systematic review linking the WEF nexus to clean energy transitions, found that renewable energy deployment consistently generates cross-system co-benefits when planned with nexus – awareness – a finding directly relevant to Madagascar's off-grid solar opportunity.

Nkiaka et al. (2023) applied the WEF Nexus Index to all 54 African nations, finding that sub-Saharan countries cluster around a pattern of simultaneous water-energy-food insecurity in which governance capacity, not physical endowment, predicts performance variation. *Authier et al. (2024)*, in the most methodologically proximate study to the present paper, applied a combined Geographic Information System (GIS) and optimization model to the Water-Energy-Food (WEF) nexus of Réunion Island – a comparable small island in the Indian Ocean context – demonstrating that land use competition between food, water, and energy systems can be quantified and mitigated through integrated spatial planning. Their finding that dietary behaviours are closely interlinked with land use competition is directly applicable to Madagascar's tavy-rice culture.

(Tavy is the Malagasy term for slash-and-burn agriculture – the practice of clearing forest by fire to create temporary cultivation plots, predominantly for upland rice. The tavy-rice manner thus refers to the structural interdependence between this deforestation-driven cultivation system and Madagascar's broader food, water, and energy dynamics: tavy provides subsistence food security to millions of smallholders while simultaneously driving the deforestation, watershed degradation, and soil erosion that undermine long-term agricultural and hydropower viability.) *Chagwiza et al. (2025)*, in a global systematic review of 117 empirical nexus studies, found that the most recent research direction extends the WEF nexus to incorporate soil and biodiversity resources whose degradation in Madagascar directly drives nexus failure.

For Madagascar specifically, *Barrett et al. (2025)* documented that annual precipitation declined at 14 of 15 long-term weather stations between 1961 and 2017, with temperatures projected to rise 3-5 °C by 2100, directly threatening rice productivity and river discharge for hydropower. *Davies et al. (2024)* found that gendered-related constraints on agricultural adaptation-lower asset ownership and, less extension access-disproportionately expose female smallholders to climate-nexus shocks. The International Monetary Fund (*IMF 2023*) integrated the Water-Energy-Food (WEF) nexus explicitly into Madagascar's macroeconomic framework, identifying the energy-water-food triad as the primary structural constraint on growth.

This paper positions itself within the governance-focused strand of nexus literature, building on the methodological approach of *Authier et al. (2024)* and the continental analytical framework of *Nkiaka et al. (2023)* to provide the first comprehensive Water-Energy-Food (WEF) nexus analysis for Madagascar at a national scale.

METHODS

Research Design

A sequential mixed-methods design was employed in four analytical stages: (i) systematic resource characterization, (ii) quantified nexus interdependency mapping, (iii) climate stress modulation analysis, and (iv) governance assessment and recommendation synthesis. The design follows *Bizikova et al. (2013)* for practical nexus planning and *Leck et al.'s (2015)* governance audit framework for the institutional dimension.

Data Collection

Secondary data were systematically retrieved from eight institutional databases, prioritizing 2018-2024 records: *FAO AQUASTAT (2022)* (water withdrawals, irrigation coverage), *World Bank 2023* (electrification, poverty, arable land), International Energy Agency (*IEA 2023*) (energy mix, renewable potential), International Renewable Energy Agency (*IRENA 2023a*), Integrated Food Security Phase Classification (*IPC 2024*) (food insecurity phase classifications), United Nations International Children's Emergency Fund (*UNICEF and WHO 2023*), Water, Sanitation and Hygiene (WASH) indicators, Global Forest Watch (*GWF 2024*), *Andriamparany et al. (2023)* (Landsat analysis-deforestation), Sustainable Energy for All (United Nations initiative) (*SE4All 2024*) (geospatial energy access), and United Nations Economic Commission for Africa and World Food Programme (*ECA and WFP 2024*) (nexus policy initiatives). Peer-reviewed literature was identified through searches in Web of Science, Scopus, and PubMed using the Boolean string: ('water-energy-food nexus' OR 'Water-Energy-Food (WEF) nexus') AND ('Madagascar' OR 'island developing' OR 'Sub-Saharan Africa') AND ('governance' OR 'food security' OR 'hydropower'). From 214 initial results, 40 studies met full inclusion criteria (empirical nexus or Madagascar-specific focus; published 2011–2025; Web of Science/Scopus indexed).

Analytical Approach

Water-Energy-Food characterization benchmarks Madagascar's indicators against Sub-Saharan African averages and Sustainable Development Goal (SDG) 2030 targets (*Table 1*). Nexus interdependency analysis constructs and quantifies five principal feedback pathways by triangulating magnitude data from multiple sources (*Table 2*). Climate stress analysis integrates Intergovernmental Panel on Climate Change (*IPCC 2022*) regional projections with station-level precipitation trend data from *Barrett et al. (2025)*. Governance assessment applies *Leck et al.'s (2015)* five-dimension audit (coordination, capacity, data, finance, accountability) to each sector and at the cross-sectoral level. Limitations include subnational WEF data available primarily for the Grand Sud and major river basins; no primary data collection; and the dynamic policy context post-2024 may not be fully captured.

Figure 1 positions Madagascar within the full cross-national distribution of the 54 Sub-Saharan African (SSA) nations covered by the WEF Nexus Index of *Nkiaka et al. (2023)*: each data point is a single SSA country-level observation for one of the three nexus dimensions (water access, energy access, food security), drawn from the same institutional databases listed above. Madagascar's values are distinguished to show where the country sits relative to the regional spread. This methodological choice is not incidental. The paper's central hypothesis – that Madagascar's nexus failures reflect institutional dysfunction rather than physical resource scarcity – can only be tested against a comparator group that shares broadly similar physical endowment levels. Plotting Madagascar within the SSA distribution allows the reader to verify directly whether its underperformance is a regional outlier or a structurally predictable outcome; if similarly endowed SSA peers achieve substantially better nexus scores, the institutional explanation gains empirical support. The figure therefore serves an evidentiary rather than illustrative function, and the data points are neither sub-national observations nor separate studies about Madagascar alone.

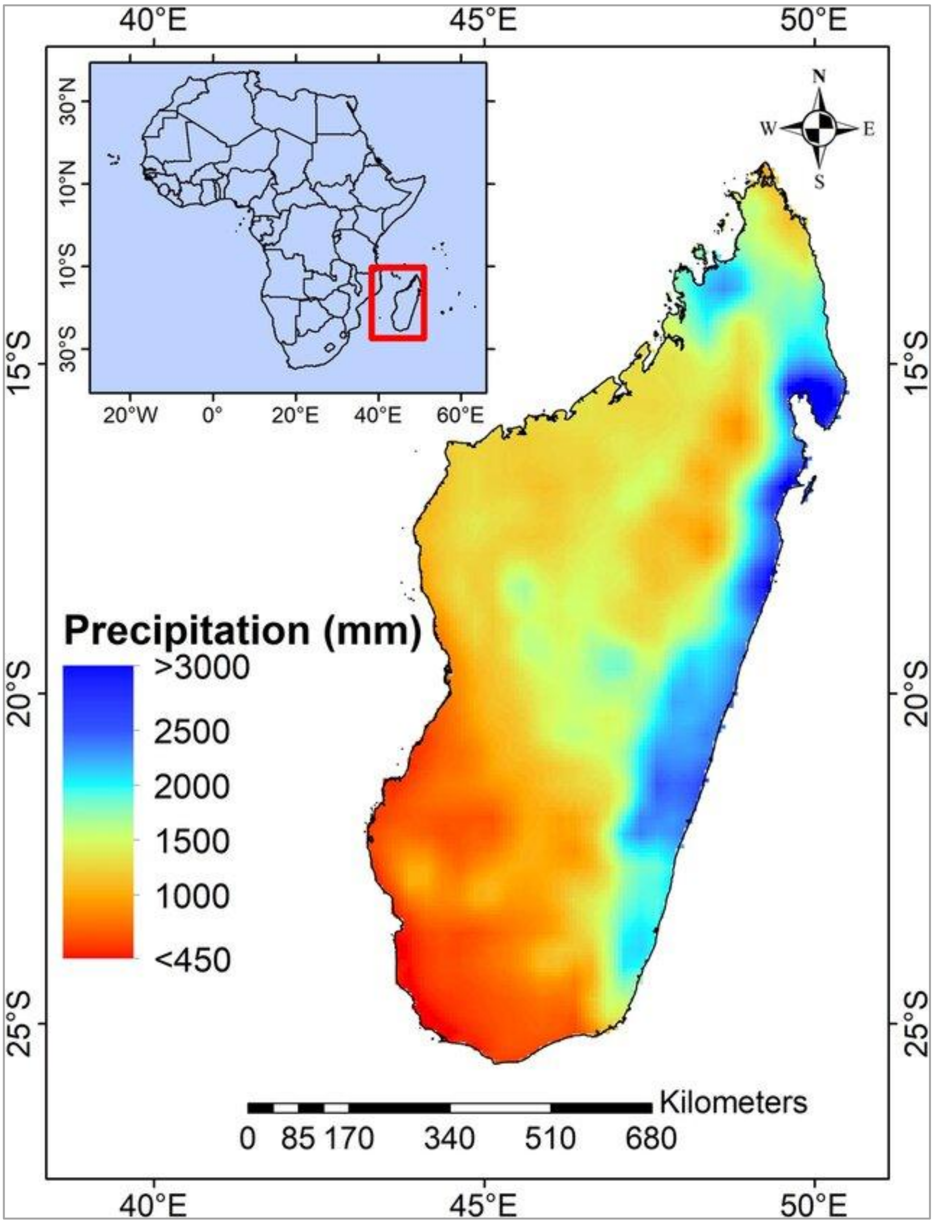


Figure 1. Spatial distribution of rainfall in Madagascar (Rabezanahary et al. 2025)
1. ábra. A csapadék területi eloszlása Madagaszkáron (Rabezanahary és társai 2025)

RESULTS

Water-Energy-Food Composite Stress Profile

Table 1 presents Madagascar's position across 12 WEF indicators benchmarked against Sub-Saharan African (SSA) averages and SDG 2030 targets. The data reveal a consistent pattern: despite national-level hydrological abundance (12,000 m³ per capita more, than double the SSA average of 5,800 m³), access as well as management performance are systematically below regional norms. Only 14% of the pop-ulation has access to safely managed drinking water com-pared with the Sub-Saharan African average of 28%; agri-cultural water withdrawals account for 96% of total fresh-water use, substantially exceeding the regional average of approximately 70%, indicating limited water availability for domestic and industrial uses. While the SSA average, in-cludes countries with markedly different socioeconomic and water management contexts, including South Africa, Mada-gascar remains among the region's poorest-performing countries on both indicators. The electrification deficit is equally stark: at 33.7% national and 6–10% rural rates, Madagascar trails the SSA average (48.4%) despite pos-sessing 7,800 MW of hydropower potential, of which only 162 MW 2.1% is currently exploited. Biomass constitutes approximately 85% of primary energy, versus an SSA aver-age of 68%, confirming Madagascar as a high-end outlier on traditional energy dependence. In the food dimension, 1.63 million people (15% of the population analysed) faced IPC Phase 3 or above food insecurity between September and December 2024, with 48,000 in Emergency (Phase 4); child stunting stands at 47% one of the five highest rates globally and post-harvest rice losses of 20-30% compound production deficits. Critically, the resource endowment col-umns (freshwater per capita, solar irradiation, hydropower potential) indicate that these outcomes are governance and infrastructure failures – not scarcity failures a finding that directly supports the central hypothesis.

Table 1. WEF Composite Stress Profile: Madagascar vs. SSA Benchmarks and SDG 2030 Targets (author' compilation based on cited databases)

1. táblázat. Víz-Energia-Élelmiszer (WEF) összetett stresszprofil: Madagaszkár vs. Szubszaharai Afrikára vonatkozó referenciaértékek és a 2030-as fenntartható fejlődési célok (a szerző szerkesztése a hivatkozott adatbázisok alapján)

Indicator	Madagascar	SSA Average	Target 2030	Source
Freshwater per capita (m^3/yr)	11,072 – 13,179	~5,800	-	*FAO AQUASTAT (2022)*
Basic drinking water access (%)	53 – 55.8	70	100	*UNICEF and WHO (2023)*
Safely managed water (%)	22	28	100	*UNICEF and WHO (2023)*
Agricultural water share (%)	96	70	<85	*FAO AQUASTAT (2022)*
National electrification rate (%)	36	48.4	70	*ADB and World Bank (2023)*
Rural electrification rate (%)	5 - 7	28	70	*ADB and IEA (2023)*
Traditional biomass share (primary energy) (%)	80 ~ 90	~68	<50	*IEA (2023)*
Hydropower exploited / potential	162 MW/7,800 MW	n/a	≥2,000 MW	*IRENA (2023b)*
IPC Phase 3+ (Sep–Dec 2024)	1.63 M (15%)	Variable	< 5%	*IPC (2024)*
Child stunting (<5 yrs)	39 - 42 %	~35%	<10%	*WBG and WFP (2024)*
Post-harvest food losses (rice)	11,4 %	15–20%	<10%	*APHLIS and USAID (2020)*
Tree cover lost since 2000	4.85 Mha (25%)	Varies	Net zero loss	*Andriamparany et al. (2023)*

Nexus Interdependency Analysis

Table 2 quantifies five principal nexus feedback pathways identified through data triangulation. The dominant cascade is the biomass-deforestation-hydropower loop: charcoal and fuelwood demand (85% of primary energy) drives forest clearance at approximately 260 000 ha/year (*GFW 2024*), stripping riparian catchment cover, elevating erosion rates, and increasing sediment loads in rivers that feed Madagascar's hydropower infrastructure. The Betsiboka River now carries sediment concentrations, which are among the highest recorded globally. In drought years, this sedimentation-weakened system faces additional stress: dry-season river discharge in western and central catchments can decline 70–80% from wet-season peaks, reducing hydropower output and triggering load-shedding events of 12+ hours/day in Antananarivo, disabling the irrigation pumps, cold storage systems, and milling equipment that food security depends upon.

Table 2. Quantified Water-Energy-Food (WEF) nexus feedback pathways in Madagascar (author' compilation based on cited references)

2. táblázat. Mennyiségileg meghatározott víz-energia-élelmiszer (WEF) nexus visszacsatolási útvonalak Madagaszkáron (a szerző szerkesztése a hivatkozott hivatkozások alapján)

Nexus Pathway	Mechanism	Quantified Impact (Madagascar)	Key Reference
Deforestation → Hydropower	Sedimentation degrades reservoir capacity & turbine efficiency. But it also increases mean runoff at the same time	~260 kha natural forest lost/yr; dry-season load-shedding ≥12 h/day in drought years	*GFW (2024)* *Andriamparany et al. (2023)* *Moran et al. (2018)*
Energy deficit → post-harvest loss	No cold chain, no mechanical drying; rice sold at harvest-trough prices	20-30% rice post-harvest loss; 25-40% reducible with village electrification	*USAID (2020)* *IEA (2023)*
Deforestation + Drought → Hydropower → Food cascade	Deforestation increases runoff and flow variability while reducing dry-season baseflow; combined with recurrent drought, dry season discharge ↓70–80%; energy shortfall → pump failure → irrigation collapse	1.94 M people projected IPC ≥3 in lean season 2025; Grand Sud rainfall –5 to –10% by 2100	*IPC (2024)* *Barrett et al. (2025)*
Water-smart irrigation → Food security	Irrigated rice yields 3–4× rainfed; SRI (System of Rice Intensification) can increase yields 50–100%	60% of 1.5 Mha rice under irrigation; Lac Alaotra basin = 15% of national rice output	*FAO AQUASTAT (2022)* *FAO (2021)*
Biomass demand → Deforestation → Water	Charcoal harvesting strips riparian vegetation; accelerates erosion and sedimentation	85% primary energy from biomass; Betsiboka River sediment loads among highest globally	*IEA (2023)* *Scales (2012)*

The second critical pathway is the energy-to-food value chain gap. Post-harvest losses of 20-30% of rice production result directly from the absence of mechanical drying, milling, and cold storage, all of which require reliable electricity. *IEA (2023)* evidence from comparable Sub-Saharan contexts suggests that village-level electrification reduces such losses by 25-40%, implying that the energy deficit is effectively destroying between 375 000 and 750 000 tons of rice-equivalent output per year. The third pathway, smart irrigation represents the most tractable synergy: irrigated rice yields 3-4 times those of rain-fed cultivation, yet the Lac Alaotra basin, supplying 15% of national rice output, is experiencing documented reservoir capacity decline from sediment accumulation (*Scales 2012*), and much of the south receives fewer than 400 mm of annual rainfall, making irrigation infrastructure – not water per se – the binding constraint.

A gender dimension intersects all pathways. *Davies et al. (2024)* documented those female smallholders in Madagascar face systematically lower adaptation capacity than male counterparts due to asset constraints, limited extension access, and higher labour burdens in water and biomass collection. Since women manage approximately 70% of smallholder food production, these gender-nexus interactions have first-order food security implications that uniform policy instruments will not adequately address.

Climate Change Amplification

Madagascar's climate trajectory compounds all five nexus pathways. *Barrett et al. (2025)* documented precipitation declines at 14 of 15 long-term weather stations between 1961 and 2017, with temperature increases observed at all locations. Northeast Madagascar a key agricultural zone faces projected annual rainfall declines of 5–10% and temperature increases of 3–5 °C by 2100 under RCP (Representative Concentration Pathway) 4.5 and RCP 8.5 scenarios, respectively. These trends will alter the distribution of forested areas and reduce rice yields across the island's primary growing zones. For the Grand Sud, three consecutive years of below-average rainfall (2020-2023) produced the worst drought in 40 years, pushing 1.71 million people to IPC Phase 3+ at its peak and prompting UN agencies to describe it as a climate-attribution famine event-the first of its kind globally (*FAO and WFP 2022*).

Cyclonic events constitute a second climate-nexus amplifier operating at an event scale. Cyclone Gamane (in 2024) affected approximately 535,000 people in 33 flooded communes in northeast Madagascar, damaged approximately 1,700 hectares of rice cultivation, and disrupted both energy infrastructure and water supply systems simultaneously (*CRI 2024*). This simultaneous cross-system disruption illustrates how climate shocks propagate through nexus linkages: crop loss increases food insecurity; infrastructure damage disables pumping and cold storage; and post-event recovery deforestation accelerates sediment loads. The *IPCC (2022)* projects increased frequency and intensity of southern Indian Ocean tropical cyclones under higher emissions scenarios, meaning this event-scale nexus disruption will become more frequent.

Evaluation of the Central Hypothesis

As a result, Madagascar's per capita renewable freshwater endowment exceeds the global scarcity threshold by a factor of seven, yet safely managed water access stands at 14% – evidence that water poverty is a governance, infrastructure, and finance failure, not a supply failure. Hydropower potential of 7 800 MW dwarfs current installed capacity of 162 MW; the binding constraint is not hydrology but investment, regulatory capacity, and catchment management. Food production is constrained not by cultivable land area (3.0 million hectares of arable land exist) but by the combined failures of irrigation infrastructure, post-harvest energy, and transport connectivity, all of which are institutional. *Nkiaka et al. (2023)* reached an analogous conclusion for Sub-Saharan Africa broadly, finding governance capacity to be the dominant predictor of WEF nexus performance variation; the Madagascar-specific data presented here provide a quantified case study confirming this pattern at national level.

DISCUSSION

Comparison with Island Nexus Literature

Authier et al.'s (2024) GIS-optimization study of Réunion Island-geographically comparable to Madagascar (both Indian Ocean islands, with similar rainfall asymmetry between windward and leeward coasts) – found that WEF nexus land-use competition on small islands can be significantly reduced through integrated spatial planning that aligns renewable energy infrastructure locations with watershed protection and food production zones. Madagascar shares the structural feature of concentrated resource pressure on a limited land area but operates at 15 times Réunion's population scale with a fraction of its institutional capacity. The transferable insight is methodological: geospatial optimization at the commune level, as currently being developed through the *ECA and WFP (2024)* initiative, offers a tractable pathway to the kind of evidence-based nexus planning that *Authier et al. (2024)* demonstrate is feasible even in resource-limited island contexts.

The Biomass Trap as a Policy Priority

The biomass-deforestation-hydropower cascade identified in *Table 2* is the highest-priority nexus intervention target because it is simultaneously the dominant energy pathway, the primary deforestation driver, the main source of hydrological degradation, and a major contributor to food security failures through irrigation and cold-chain impairment. *Herrera-Franco et al. (2024)* demonstrated, in a systematic review linking the WEF nexus to clean energy transitions, that off-grid solar deployment consistently produces nexus co-benefits beyond the direct energy access effect: by substituting for biomass cooking, it reduces deforestation pressure; by enabling agricultural productive use, it improves irrigation efficiency and reduces post-harvest losses; and by reducing the labour burden of biomass collection (which falls primarily on women), it improves food production capacity. The Sahofika (205 MW) and Volobe (120 MW) hydropower projects, while transformative for grid electricity supply, do not address the biomass trap for the 66.3% of the population without electricity access. Off-grid solar, as *SE4All (2024)* confirmed through Madagascar's Integrated Energy Access Planning (IAP) process, is the cost-effective pathway for rural areas, but only if paired with productive use incentives and cold-chain subsidies.

Governance Architecture: What the Evidence Supports

Three governance reforms are directly supported by the evidence. First, the *ECA and WFP (2024)* initiative demonstrates that cross-ministerial nexus coordination is feasible: the joint engagement of the Ministries of Agriculture, Energy, and Hydrocarbons, and the National Mapping Agency under a shared geospatial analytical framework constitutes a de facto nexus planning platform that requires only formalization and resourcing to become a standing coordination mechanism. Second, the Forest Carbon Partnership Programme *FCPF (2024)* targeting a 40% deforestation reduction with an 11.8 $MtCO_2e$ emissions baseline and USD 50 million results-based payment provides an existing financial mechanism whose performance metrics could be expanded to capture downstream water and food security co-benefits, creating a results-based nexus finance instrument. Third, the *World Bank (2024)* (LEAD Project) model providing concessional household electricity connections at a 30% cost reduction demonstrates that innovative access pricing can overcome the affordability barrier in urban and peri-urban areas, a model ADER could adapt for rural mini-grids with agricultural productive-use requirements embedded in concession design.

CONCLUSION

This paper has provided the first comprehensive, data-grounded WEF nexus analysis of Madagascar, structured around an interrelated problem statement, testable hypothesis, and four research questions. The central hypothesis – that institutional fragmentation, not physical resource scarcity, is the binding constraint on Madagascar's WEF nexus performance is strongly supported by the evidence. Mad-agascar's water abundance (12 000 m³ per capita/ year) co-exists with 14% safely managed water access; its 7 800 MW hydropower potential coexists with 66.3% energy poverty; and 3.0 million hectares of arable land coexist with a 47% child stunting rate.

The five identified nexus feedback loops reveal that the biomass-deforestation-hydropower cascade is the systemic linchpin: disrupting it through off-grid solar deployment, upstream catchment restoration paired with the Sahofika and Volobe hydropower investments, and formalization of the ECA-WFP cross-sectoral coordination platform would simultaneously improve energy access, hydrological stability, irrigation reliability, and post-harvest food chain performance. Climate change is accelerating all five feedback loops and concentrating the costs on the most food-insecure and climate-exposed communities in the Grand Sud.

Three recommendations are directly evidence-supported: (i) formalize the *ECA and WFP (2024)* geospatial nexus initiative as a standing National Water-Energy-Food (WEF) Coordination Secretariat; (ii) embed nexus co-benefit metrics into the FCPF deforestation payment framework to create an integrated water-food-energy finance instrument; and (iii) adopt productive-use requirements in ADER rural electrification concessions to ensure off-grid solar deployment, which in turn generates food security and water management co-benefits at scale. Future research should prioritize commune-level nexus mapping using the SE4All geospatial platform, longitudinal evaluation of the Sahofika and Volobe projects as natural experiments, and gendered disaggregation of nexus outcomes.

REFERENCES

Andriamparany, J.N., Razafindramanana, J., Ralimanana, H. (2023). Status of deforestation in Madagascar (2001–2021): Landsat time-series analysis. Biological Conservation, 278, 109907. https://doi.org/10.1016/j.biocon.2023.109907

Authier, R., Pillot, B., Guimbretière, G., Corral-Broto, P., Gervet, C. (2024). Towards sustainable land management in small islands: A Water-Energy-Food nexus approach. PLOS ONE, 19(11), e0310632.
https://doi.org/10.1371/journal.pone.0310632

Barrett, T.M., Soarimalala, V., Pender, M., Kramer, R.A., Nunn, C. L. (2025). Climate change perceptions and adaptive behavior among smallholder farmers in northeast Madagascar. PLOS Climate, 4(3), e0000501.
https://doi.org/10.1371/journal.pclm.0000501

Bizikova, L., Roy, D., Swanson, D., Venema, H.D., McCandless, M. (2013). The water–energy–food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management. IISD. ISBN: 978-1-894784-42-2.

Chagwiza, C., Murandu, T., Mutambara, S. (2025). A global systematic review of resource nexus and nature-positive sustainable development. Sustainability Science, 20(2), pp. 1-18.
https://doi.org/10.1080/27658511.2025.2554480

CRI (2024). Impacts of climate change and hazards on key sectors in Madagascar. Crisis and Resilience Institute.
https://cri-world.com/publications/qed_dp_4626.pdf

Davies, B., Randrianasolo, H., Rajaonarison, M. (2024). Gendered implications for climate change adaptation among farmers in Madagascar. Climate and Development, 16(4), pp. 297-314.
https://doi.org/10.1080/17565529.2024.2363377

ECA and WFP (2024). ECA, WFP explore renewable energy solutions for enhanced food security in Madagascar. 2024. March 15. UN Economic Commission for Africa. https://www.uneca.org/stories/eca,-wfp-explore-renewable-energy-solutions-for-enhanced-food-security-in-madagascar

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. https://www.fao.org/3/bl581e/bl581e.pdf

FAO (2021). Madagascar: Country brief on nutrition. Food and Agriculture Organization. https://www.fao.org/countryprofiles/index/en/?iso3=MDG

FAO AQUASTAT. (2022). AQUASTAT country profile: Madagascar. FAO. https://www.fao.org/aquastat/en/countries-and-basins/country-profiles/country/MDG

FAO and WFP (2022). Crop and food supply assessment mission to southern Madagascar. FAO/WFP. https://www.wfp.org/publications/southern-madagascar-cfsam-2022

FCPF (2024). Madagascar country profile. Forest Carbon Partnership Facility, World Bank. https://www.forestcarbonpartnership.org/sites/default/files/documents/madagascar_country_profile_fcpf.pdf

GFW (2024). Madagascar deforestation rates and statistics. Global Forest Watch. https://www.globalforestwatch.org/dashboards/country/MDG/

Herrera-Franco, G., Bravo-Montero, L., Caicedo-Potosí, J., Carrión-Mero, P. (2024). A sustainability approach between the Water-Energy-Food nexus and clean energy. Water, 16(7), 1017. https://doi.org/10.3390/w16071017

Hoff, H. (2011). Understanding the nexus. Background paper for the Bonn 2011 Conference: The water, energy and food security nexus. Stockholm Environment Institute. https://www.sei.org/publications/understanding-the-nexus/

IEA (2023). Africa energy outlook 2023. International Energy Agency. https://www.iea.org/reports/africa-energy-outlook-2023

IMF (2023). Food insecurity and climate shocks in Madagascar (Selected Issues Papers, Vol. 2023, Issue 037). IMF. https://doi.org/10.5089/9798400236464.018

IPC (2024). Madagascar: Acute food insecurity situation for September–December 2024 and projections for January–August 2025. Integrated Food Security Phase Classification. https://www.ipcinfo.org/ipc-country-analysis/en/?country=MDG

IPCC (2022). Climate change 2022: Impacts, adaptation and vulnerability (H.-O. Pörtner et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009325844

IRENA (2023a). Renewable energy statistics 2023. International Renewable Energy Agency. ISBN: 978-92-9260-584-8.

IRENA (2023b). Energy profile: Madagascar. IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Madagascar_Africa_RE_SP.pdf

Leck, H., Conway, D., Bradshaw, M., Rees, J. (2015). Tracing the water-energy-food nexus: Description, theory and practice. Geography Compass, 9(8), pp. 445–460. https://doi.org/10.1111/gec3.12222

Minten, B., Barrett, C.B. (2008). Agricultural technology, productivity, and poverty in Madagascar. World Development, 36(5), pp. 797-822. https://doi.org/10.1016/j.worlddev.2007.05.004

Moran, E.F., Lopez, M.C., Moore, N., Müller, N., Hyndman, D.W. (2018). Sustainable hydropower in the 21st century. Proceedings of the National Academy of Sciences, 115(47), pp. 11891-11898. https://doi.org/10.1073/pnas.1809426115

Nematchoua, M.K. (2020). A study of climate change and energy consumption in Madagascar island. Health and Environment, 1(1), pp. 1-12. https://doi.org/10.25082/HE.2019.01.002

Nkiaka, E., Bryant, R.G., Manda, S., Okumah, M. (2023). An African perspective on the Water-Energy-Food nexus. Scientific Reports, 13(1), 16781. https://doi.org/10.1038/s41598-023-43606-9

Rabezanahary, T., Jun, Z., Andrianarimanana, M. (2025). Evaluation of the Performance of HighResMIP CMIP6 in Simulating Extreme Precipitation in Madagascar. International Journal of Climatology. V45. DO - 10.1002/joc.70011. https://doi.org/10.1002/joc.70011

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. Environmental Development, 18, pp. 14–25. https://doi.org/10.1016/j.envdev.2015.12.001

Scales, I.R. (2012). Lost in translation: Conflicting views of deforestation, land use and identity in western Madagascar. The Geographical Journal, 178(1), pp. 67-79. https://doi.org/10.1111/j.1475-4959.2011.00432.x

SE4All (2024). Madagascar integrated energy access planning: Clean cooking report. Sustainable Energy for All. https://www.seforall.org/system/files/2024-07/report-madagascar-iep_cleancooking-en.pdf

UNICEF and WHO (2023). Progress on household drinking water, sanitation and hygiene 2000–2022. WHO/UNICEF JMP. https://www.who.int/publications/i/item/9789240060272

USAID (2020). Madagascar feed the future country plan. USAID. https://www.usaid.gov/madagascar/food-assistance

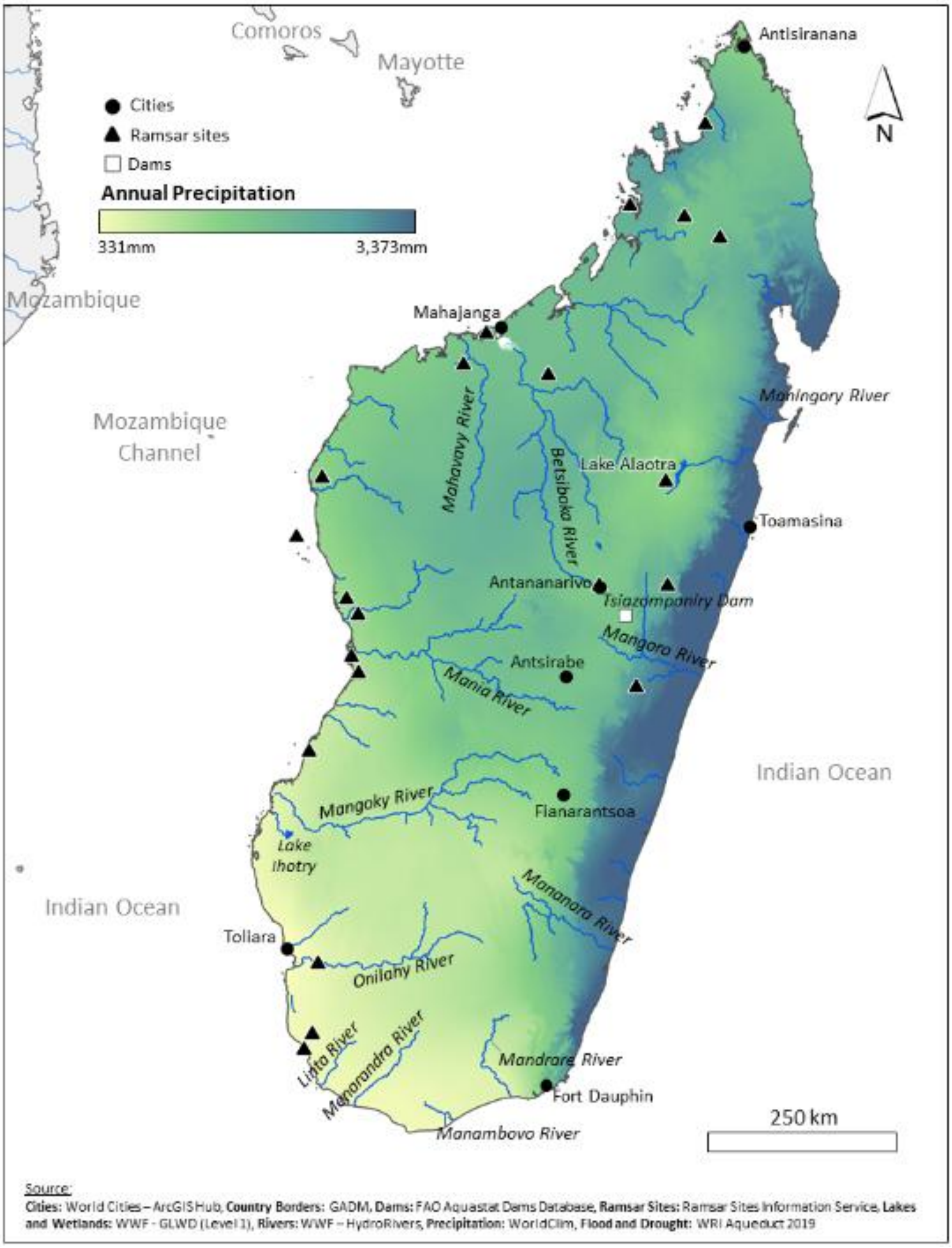
WFP (2024). Madagascar country strategic plan 2022–2025. World Food Programme. https://www.wfp.org/operations/mg02-madagascar-country-strategic-plan-2022-2025

World Bank (2023). Madagascar climate and development report. World Bank Group. https://openknowledge.worldbank.org/handle/10986/madagascar-ccdr

World Bank. (2024) Energy access in Madagascar: LEAD Project brief. World Bank Group. https://www.worldbank.org/en/news/video/2024/09/19/energy-access-in-afe-madagascar

AUTHOR

ROVATIANA SALEMA ANDRIANASOLOMAHEFA has been a PhD student at the Doctoral School of Public Administration Sciences, Faculty of Public Governance and International Studies, Ludovika University of Public Service (LUPS), Budapest, Hungary, since 2024. He holds a Master's degree in Applied Geophysics from the University of Antananarivo, Madagascar, and a Master's degree from the National School of Administration (ENAM), Madagascar. Before joining LUPS, he worked for the Ministry of Water, Sanitation and Hygiene of Madagascar as a hydrogeological and water resources specialist and later served in the Ministry of National Education in public procurement and project management. His research focuses on water governance, Integrated Water Resources Management (IWRM), the Water–Energy–Food (WEF) Nexus, institutional reform, and climate-resilient water governance in Madagascar.



Madagascar's water resources (https://winrock.org/wp-content/uploads/2021/08/Madagascar_Country_Profile-Final.pdf)
Madagaszkár vízkészletei (https://winrock.org/wp-content/uploads/2021/08/Madagascar_Country_Profile-Final.pdf)