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Impact of Flood Events on the Water–Food–Energy Security for Hydropower Dams along the River Niger Basin

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Systematic Review

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Impact of Flood Events on the Water–Food–Energy Security for Hydropower Dams along the River Niger Basin

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Abstract

Hydropower dams in the River Niger Basin face escalating flood risks driven by climate change and upstream watershed degradation. These dams are critical for energy security, water regulation, and food systems across one of Africa's most populous transboundary basins. This review evaluates flood impacts through a Water–Food–Energy (WFE) nexus lens, investigating how extreme hydrological events generate cascading liabilities across sectors that single-sector assessments systematically underestimate. A systematic literature review was conducted using SCOPUS, Web of Science, ScienceDirect, Google Scholar, and institutional databases, synthesizing findings from 75 peer-reviewed publications. The analysis reveals that flood-induced spillway releases, while necessary for dam safety, simultaneously degrade downstream water quality, inundate floodplain agriculture, reduce fisheries productivity, and curtail hydropower generation. Sediment-laden flood pulses accelerate reservoir capacity loss and undermine irrigation reliability. At the same time, energy-sector disruptions propagate into food systems through irrigation pump failures, cold chain interruptions, and processing facility downtime. Transboundary governance gaps further amplify downstream vulnerabilities. The review concludes that engineering-centric or energy-focused flood management overlooks critical basin-wide nexus interdependencies. Effective adaptation requires integrated operational protocols and WFE-sensitive risk assessment frameworks that align dam safety with cross-sectoral resilience.

Keywords: Water–food–energy nexus; flood impacts; hydropower dams; River Niger Basin; transboundary water security; cascading risks.

Introduction

Hydropower is a major part of the world's renewable energy, accounting for approximately 50% of global renewable energy and providing around 15% of the world's electricity generation [1, 2]. Hydropower is crucial for reducing energy poverty, boosting economic growth, and fostering cooperation among African countries [3]. Large dams play a significant role in managing water resources for both domestic consumption and agricultural production. Reservoir operating policies are closely linked to the agricultural systems and ecosystems in the surrounding areas [4, 5]. This linkage is referred to as the water–food–energy nexus, as shown in Fig. 1, which highlights how changes or policies in one area can have a ripple effect on the others [6].

Flooding constitutes a major environmental challenge in West Africa, with climate change, deforestation, unsustainable land use, and rapid urbanization having increased flood frequency and intensity [7, 8, 9]. While hydropower dams are engineered to manage hydrological variability, they remain susceptible to extreme flood events. Excessive inflows can threaten dam safety, necessitate emergency water releases, disrupt electricity generation, and destabilize regional energy systems [10, 11]. Additionally, such flood events degrade water quality, inundate agricultural land, and disrupt fisheries, impacts that are frequently inadequately addressed in conventional dam-risk assessments. The River Niger Basin (NRB) spans nine riparian countries: Guinea, Mali, Côte d'Ivoire, Burkina Faso, Niger, Benin, Nigeria, Cameroon, and Chad, covering a drainage area of approximately 2,170,500 km² [3]. The basin encompasses varied climatic zones, from humid tropical regions to semi-arid Sahelian landscapes, and supports a

population exceeding 100 million, with 64% residing in rural areas [5]. Agriculture is the primary economic activity, contributing 25–35% of GDP, while livestock and fisheries account for 10–15% and 1–4%, respectively [5].

The Niger Basin Authority (NBA), established in 1980, is responsible for coordinating sustainable development across the water, energy, agriculture, and environmental sectors; however, institutional fragmentation remains a major challenge [4]. The basin's hydropower potential is estimated at nearly 30,000 GWh annually, yet only 20% has been developed. Continued investments in large reservoir projects aim to address rising energy and food demands and manage high interannual water variability [2]. These trends highlight the need for integrated flood risk management that explicitly addresses cross-sectoral security trade-offs.

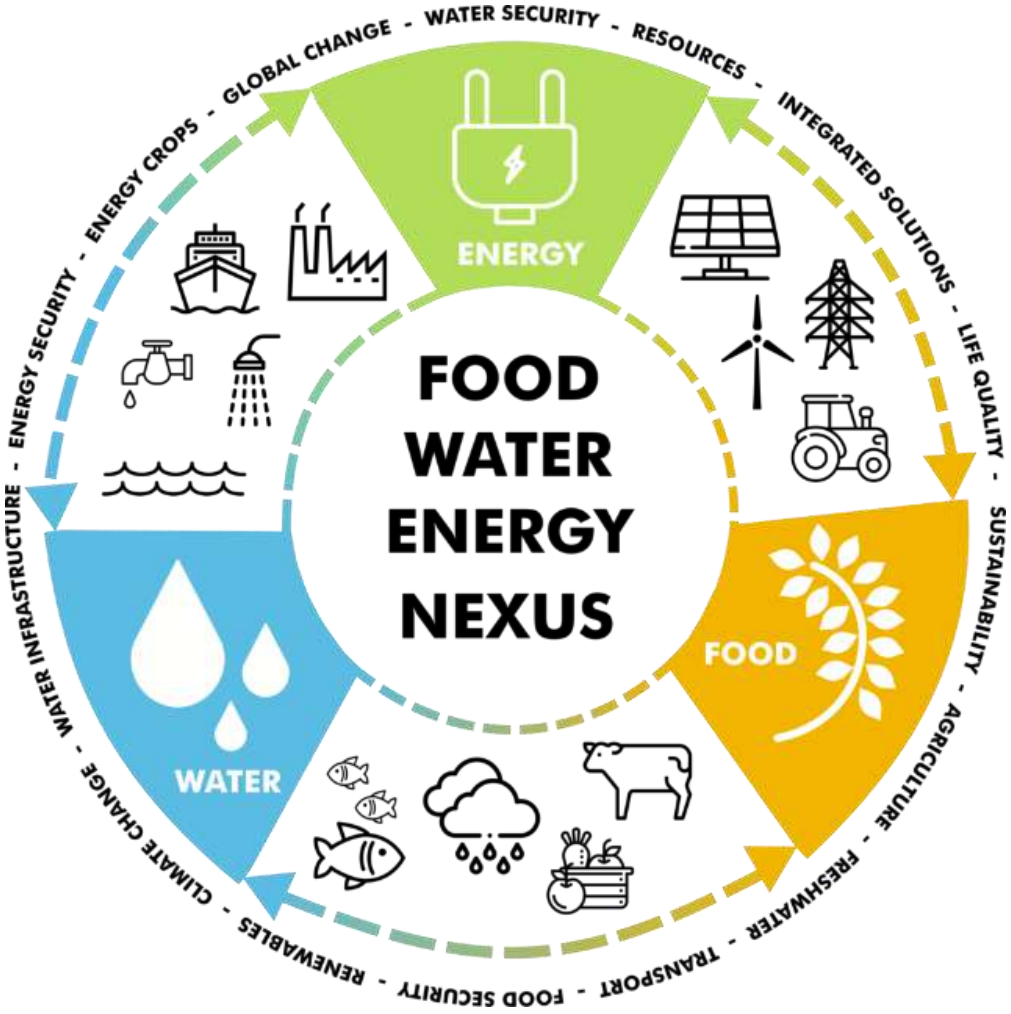


Fig. 1 A water-energy-food security nexus framework showing water, energy, and food interdependencies. *Source: adapted from Hoff (2011) and created by the authors.*

The existing body of literature on the River Niger Basin has largely developed along disciplinary trajectories, with hydrological studies characterizing flood regimes [12, 13], engineering assessments focusing on dam structural integrity during extreme inflows [14, 15], and agricultural economics documenting crop losses and fishery declines [16, 17], all without systematically interrogating their causal interconnections. While the water–food–energy nexus has been conceptually recognized in global policy discourse [6], its application to flood risk management at

hydropower dams within the Niger Basin remains nascent and insufficiently operationalized. This fragmented approach masks the complex, non-linear interdependencies that define the basin's socio-ecological system and underestimates the true cost of flood events.

This review explicitly addresses this fragmentation by defining its scope as the WFE nexus impacts of flood events at the basin's major multipurpose hydropower dams, Kainji (760 MW), Jebba (578 MW), and Shiroro (600 MW), with a cross-border extension to the Lagdo Dam in Cameroon to capture transboundary cascades. Our analysis is constrained to peer-reviewed evidence and authoritative institutional reports published between 2000 and 2026 that quantify flood-related effects on water quality and availability, agricultural and fisheries productivity, and hydropower generation and grid reliability. This review examines the impacts of flood events on water, food, and energy security at hydropower dams within the River Niger Basin. The analysis frames flooding within the WFE nexus, investigating how hydrological extremes at dam infrastructure generate cascading effects on water quality and availability, agricultural production and fisheries, and electricity generation and grid stability. The findings demonstrate that flood impacts in the Niger Basin cannot be effectively managed through single-sector approaches. Effective adaptation requires risk assessment systems that integrate food and water security externalities into dam safety and energy dispatch decisions.

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2 Study Area

2.1 Basin Characteristics

The River Niger Basin (NRB) is one of Africa's most significant transboundary river systems, spanning nine riparian countries: Guinea, Mali, Ivory Coast, Burkina Faso, Niger, Benin, Nigeria, Cameroon, and Chad as shown in Fig. 2. Covering a drainage area of approximately 2,170,500 km², the basin traverses diverse climatic zones, from humid tropical regions to semi-arid Sahelian landscapes [3]. The Niger River, the third largest in Africa, originates in the highlands of Guinea and Sierra Leone, flows through the Inner Delta in Mali, and merges with the Benue River in Nigeria before discharging into the Atlantic Ocean via the Niger Delta [5]. Table 1 summarizes the key characteristics of the River Niger Basin.

Table 1 Key Characteristics of the River Niger Basin [5, 13, 2, 3]

Characteristic	Value
Total drainage area	2,170,500 km²
River length	4,180 km
Riparian countries	9
Hydropower potential	approximately 30,000 GWh/year
Current hydropower exploitation	approximately 20%
Major existing dams	Kainji, Jebba, Shiroro, Lagdo

Characteristic	Value
Major planned dams	Kandadji, Fomi, Taoussa

The basin supports a population exceeding 120 million [18], with approximately 64% residing in rural areas [5]. Agriculture dominates the local economy, contributing 25–35% of GDP, while livestock and fisheries account for 10–15% and 1–4%, respectively [5]. The Niger Basin Authority (NBA), established in 1980, coordinates sustainable development across water, energy, agriculture, and environmental sectors among all nine riparian nations.

2.2 Study Design and Scope

This study uses a WFE nexus impact assessment to evaluate the influence of flood events at major hydropower dams on water, food, and energy systems in the River Niger Basin. The analysis focuses on three principal multipurpose dams in Nigeria: Kainji (760 MW), Jebba (578 MW), and Shiroro (600 MW), selected for their regional significance in hydropower supply, lower reach water regulation, and history of flood events [14, 19]. The Lagdo Dam in Cameroon is also examined to illustrate cross-border impacts, particularly referencing the 2012 Benue River flood that affected downstream Nigerian states.



Fig. 2 The River Niger Basin showing riparian countries and major river systems. *Source: Adapted from Niger Basin Authority*

A multi-perspective synthesis approach is employed to capture the complex interactions within the WFE nexus. The study investigates both physical processes, such as reservoir storage and sediment transport, and social elements, including water allocation policies, agricultural scheduling, and electricity management.

3. Methodology

A systematic literature review (SLR) was conducted using the SCOPUS, Web of Science, ScienceDirect, Google Scholar, and institutional publications from organizations including the International Energy Agency (IEA), International Commission on Large Dams (ICOLD), Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization (WMO), and the Niger Basin Authority (NBA) database to identify relevant journal publications, as it has been used by other studies [20, 21]. This was used to synthesize existing knowledge on the impacts of flood events on water, food, and energy security with hydropower dams in the River Niger Basin. The review focused on identifying the pathways through which flooding influences hydropower operations and the resulting implications for water availability, food production, and energy reliability. The SLR synthesized published scientific knowledge that has gone through a rigorous peer review process under the keyword combination 'flooding', 'flood risk', 'extreme rainfall', 'hydropower dam', 'reservoir', 'water quality', 'irrigation water', 'food security', 'agriculture', 'energy security', 'energy reliability', 'Niger Basin', 'Kainji', 'Jebba', 'River Niger'. The search strings combined Boolean operators such as AND and OR, for example, ("flood*" OR "flood risk") AND ("hydropower" OR "reservoir") AND ("water–food–energy nexus") AND ("Niger Basin").

The search for peer-reviewed papers was conducted in March 2026. In terms of exclusion criteria, duplicate records and studies unrelated to flooding and water–food–energy interactions were excluded. Articles with an access fee, those written in a language other than English, and pure engineering studies without nexus relevance were also excluded. Inclusion criteria selected peer-reviewed articles, English language publications from 2000 to 2026, studies related to floods, hydropower, water, food, and energy security. Selected studies were categorized according to their relevance to water security, food security, energy security, nexus interactions, flood management strategies, and governance dimensions. Findings were synthesized thematically to identify common impacts, trade-offs, and resilience pathways. The initial search yielded approximately 220 records. After duplicate removal and preliminary screening, 100 publications were selected for full-text assessment. Following relevance evaluation, 75 publications were retained for detailed synthesis.

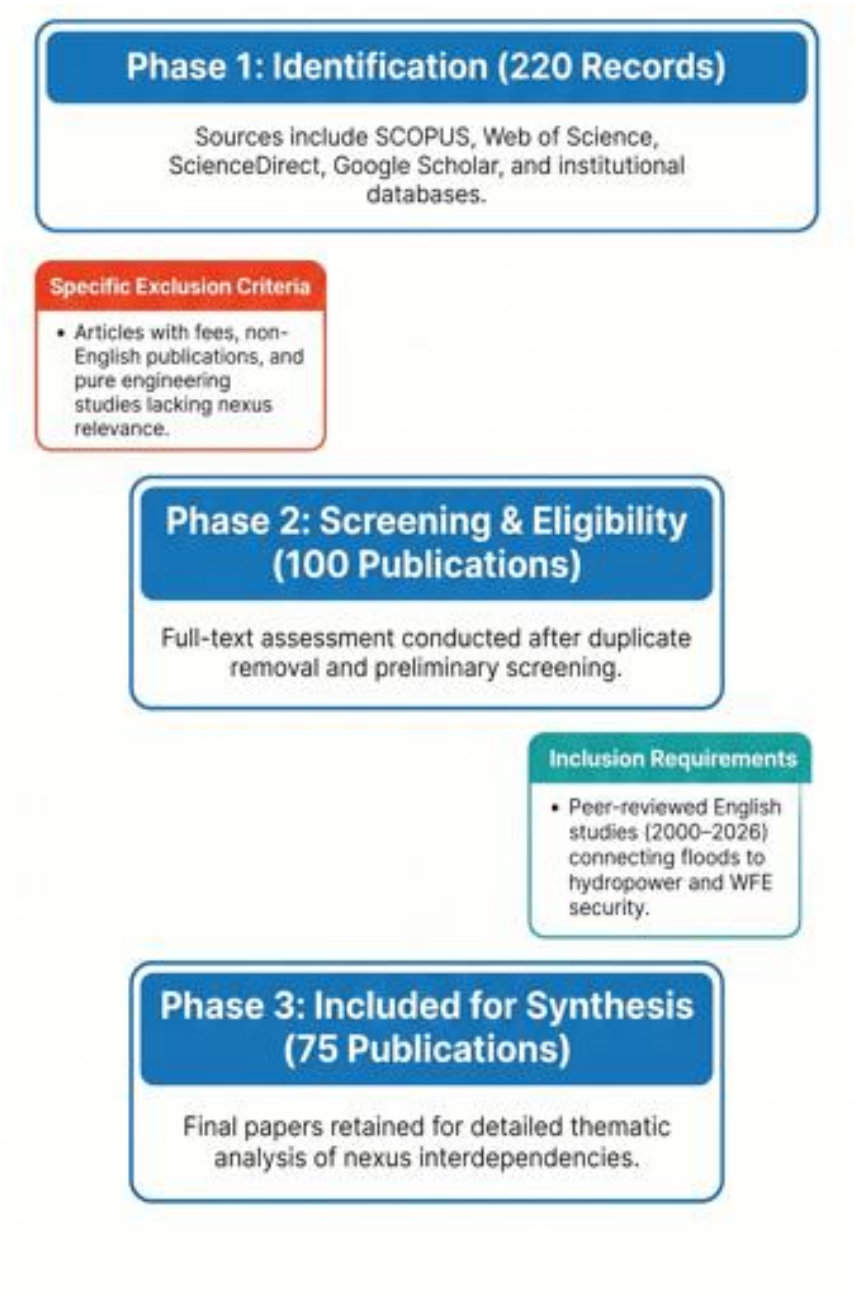


Fig. 3 Systematic literature review showing Phase 1 identification records, specific exclusion criteria, Phase 2 screening and eligibility, inclusion requirements, and Phase 3 publications included for synthesis. *Source: Original figure created by the authors.*

4. Hydrological and Flood Regime Characteristics

4.1. Hydrological and Geomorphological Setting

The Niger River is an actively changing hydrologic system driven by seasonal river flow, sediment movement, and interactions among the river, its wetlands, and floodplain lakes. Floodplain dynamics govern water distribution,

groundwater recharge, sediment deposition, and ecosystem connectivity [22, 23]. Natural flood pulses support nutrient distribution and sustain biological services, including fisheries, agriculture, and biodiversity. However, peak flow variability and upstream land development increasingly alter floodplain functionality [13, 49]. Heavy rainfall events increase surface runoff and river discharge, often causing rivers to overflow their banks and inundate surrounding floodplain environments. However, during the dry season, declining river stages disconnect marginal floodplain areas from the main channel. Stage fluctuations affect how underground and surface water interact. Elevated river stages facilitate underground water stores. Lower river levels facilitate the return of groundwater to the river.

4.2 Land-Use Change and Watershed Degradation

Anthropogenic activities, such as cutting down trees, farming, and building cities, alter how floods occur naturally. These activities reduce infiltration capacity, increase surface runoff, and modify river morphology. In northern Nigeria and the surrounding Niger Basin, changes in land use have greatly altered how water moves through the area. Vegetation removal and destruction of natural flood storage areas diminish infiltration and amplify runoff generation. Consequently, flood events become more frequent, occur earlier, and exhibit greater unpredictability, elevating flood risk in downstream areas [12, 24].

Hydrological modeling shows that the degree and frequency of floods in West African basins are projected to increase under climate change, even with constant land use. Concurrent land-use change further aggravates flood risk [13]. For example, in the Lower Niger, floods have become much worse because the natural floodplains have been altered. This has caused floodwaters to rise faster and higher, worsening conditions for people living in the area. Cumulative anthropogenic modifications in upstream catchments have altered natural hydrological processes, increasing flood severity and reducing the capacity of floodplains to store and attenuate floodwaters.

4.3 Sediment Dynamics and Reservoir Capacity Loss

Floods play an important role in sediment dynamics owing to increasing soil erosion, riverbank instability, and the transport of large quantities of suspended and bed-load sediments throughout a watershed. There is a high capacity to detach, entrain, and convey sediments from upstream areas during high-flow events, specifically in areas affected by deforestation, agricultural expansion, and land degradation. When these sediment-laden floodwaters enter reservoirs, flow velocities decrease substantially, causing sediments to settle and accumulate within the impoundment. Consequently, repeated flood events accelerate reservoir sedimentation, alter river morphology, and disrupt natural sediment transport downstream of dams [25, 26]. Sediment trapping during flood events can also affect downstream channel stability, nutrient transport, aquatic habitats, and overall river ecosystem functioning.

Floods can bring a lot of sediment into reservoirs, which takes up space that's meant for storing water. Over time, this buildup of sediment reduces the reservoir's ability to hold water, control floods, and produce hydropower. Studies have shown that this is a major problem affecting reservoirs worldwide and threatening the systems that provide us with water, energy, and food. When sediment fills a reservoir, it cannot absorb as much water during floods, which means communities downstream are more likely to flood. Also, when sediment builds up near the parts of the dam where water flows in and out, it can cause more problems and make it harder to generate hydropower, which can be very costly for the people who run the dams [27, 25, 28]. During flood peak events, the amount of sediment in the water can reach 3,500 to 4,000 milligrams per liter, especially near Niamey. This can cause significant problems for reservoirs, with some losing 0.5–1.5% of their capacity each year, especially in areas with badly degraded land [29]. If this keeps happening, a medium or large-sized hydropower reservoir could lose 10 to 30% of its storage space in just 20 to 30 years. Subsequently, the reservoir will not last as long as it should and will not produce as much electricity as it should.

5. Flood Impacts on Water Security

5.1. Water Quality Degradation

Flooding is the most frequent natural hazard globally and constitutes a significant risk to water bodies and reservoirs [30]. Flood events mobilize pathogens at the water surface and through saturated groundwater, transporting them into domestic water sources [31]. In the Niger Basin, flooding is linked to the transmission of waterborne and vector-borne diseases, including cholera, typhoid, cryptosporidiosis, and malaria. As of July 2023, the Nigeria Center for Disease Control (NCDC) reported 2,052 suspected cholera cases across 23 States, attributable to contaminated water and poor sanitation following flood events. During floods, surface water can become polluted from many different places, like areas where trash is dumped, factories that make chemicals, pesticides, and fertilizers used in farming, oil spills, septic tanks, and chemicals used in homes [32, 33].

Nigeria experienced recurrent cholera outbreaks between 2010 and 2024. The number of cases often fluctuates in a pattern, and many factors, including the time of year and environmental conditions, control this. Notably, cholera cases frequently peak during periods of heavy rainfall and flooding. Floodwater contamination of drinking water sources facilitates the transmission of *Vibrio cholerae*, the etiological agent of cholera [34, 35].

Floodwaters may either dilute contaminants or, in the presence of concentrated point sources, exacerbate pollution due to insufficient dilution capacity [36, 37]. The net effect is a deterioration of the Water Quality Index (WQI), which combines pH, conductivity, turbidity, TDS, nitrates, sulphates, chlorides, and iron into a single integrative metric [38]. Post-flood monitoring in the basin typically registers WQI values in the "poor" to "very poor" range (51–100), rendering water unsuitable for drinking without intensive treatment. For example, the 2022 floods in Northern Nigeria precipitated a major cholera outbreak. Over 10,000 people got sick, mostly in the states of Borno, Adamawa, and Yobe. The floods, poor hygiene, and contaminated water all contributed to the outbreak [39]. When floods damage water supply systems, it becomes even harder for people to access clean water, worsening the health crisis. Inadequate access to clean water not only compromises basic human needs but also undermines efforts to prevent the spread of waterborne diseases and provide essential healthcare services in flood-affected communities [40].

5.2 Eutrophication and Reservoir Water Quality

Eutrophication, characterized by high nitrogen and phosphorus concentrations that lead to algal blooms, is growing prevalent in Niger Basin reservoirs [41, 42]. Flood events exacerbate eutrophication by transporting nutrient-rich sediments and agricultural runoff into reservoirs. Rising water temperatures and decreasing wind speeds associated with climate change additionally reduce dissolved oxygen (DO) levels and stimulate algal proliferation [43, 44]. The resulting hypoxic conditions degrade aquatic ecosystems, impair raw water quality for domestic treatment plants, and increase the operational cost of water supply.

5.3 Irrigation Water Availability

Flood-induced sedimentation reduces active reservoir storage, directly diminishing the volume of water available for regulated dry-season irrigation releases. At Jebba and Kainji, emergency spillway releases during peak floods have been documented to reduce planned dry-season irrigation allocations by 15–25% in subsequent months, forcing farmers to fallow command-area plots or switch from high-value crops to less water-dependent staples [17]. Physical damage to irrigation infrastructure, blocked diversion canals, damaged pumping stations, and scoured distribution channels impose additional constraints on agricultural water security [45].

Floods frequently compromise water security by contaminating clean water sources and assisting disease transmission. Floodwaters often pollute springs and streams, leading to outbreaks of waterborne diseases such as cholera and typhoid [46, 47]. In areas near the Kainji and Jebba dams, 67.7% of residents attribute the increase in malaria incidence to dam operations [48, 49]. This issue is acute in communities like Anambra West, where many residents lack basic amenities and rely on river or stream water, which is easily contaminated during floods [47]. Regionally, only 68% of Africa's population has access to improved water supply, leaving 32% highly vulnerable to infrastructure damage and contamination from more frequent floods [49].

6. Flood Impacts on Food Security

6.1. Agricultural Production and Flood Damage

Most people living in the River Niger Basin rely on farming for their livelihood. In fact, about 64% of the people in rural areas depend on it, and it contributes a significant amount to the basin's economy, around 25–35% of the total GDP [5]. Flood events at hydropower dams affect food production through two primary pathways: First, emergency spillway releases inundate active croplands. Second, altered flow regimes disrupt the seasonal water supply upon which rain-fed and irrigated agriculture depend [49].

In the Lower Niger, floodplain farming of rice, maize, sorghum, and cowpea relies on predictable seasonal inundation followed by recession. However, uncontrolled or emergency spillway releases necessary for dam safety during extreme inflows often coincide with planting or early growth stages, destroying seedlings and leaching topsoil nutrients [24]. Conversely, delayed or reduced dry-season releases constrain recession agriculture and irrigated double-cropping. In Ghana, the government and its development partners had to rescue farmers during flooding events in August and September 2007, which resulted from the spillage of excess water from the Bagre Reservoir in Burkina Faso. Ghana's Ministry of Food and Agriculture had estimated production losses in the tune of 144,000 metric tonnes of food crops and over 70,500 hectares of farmland destroyed [50]. In Niger State and downstream of Kainji Lake, flood-induced crop losses have been severe during major event years. In 2012, floods destroyed roughly 10,000 hectares of crops [16]. In 2022, over 40,000 hectares of rice and sugarcane were submerged in a single community, and nationwide agricultural losses were estimated at 700 billion Naira (approximately USD 1.6 billion at the time) [51]. These events have displaced millions and continue to threaten food security.

Flood timing is critical: events occurring between July and September coincide with rapid growth stages of maize and sorghum, causing disproportionately higher damage compared to floods later in the season. For example, in the Middle Niger, altered flood timing from upstream dam regulation has reduced millet and rice yields by disrupting the natural flood pulse [23]. The 2012 flood in Lokoja, Kogi state, Nigeria, was particularly devastating for farmers. Adeoye [50] reported the damage it caused to their farmland and crops. Farmers reported complete inundation of yam fields, resulting in total crop failure. Rice paddies remained submerged for the entire growing season. Additionally, livestock losses were reported due to flood-related mortality.

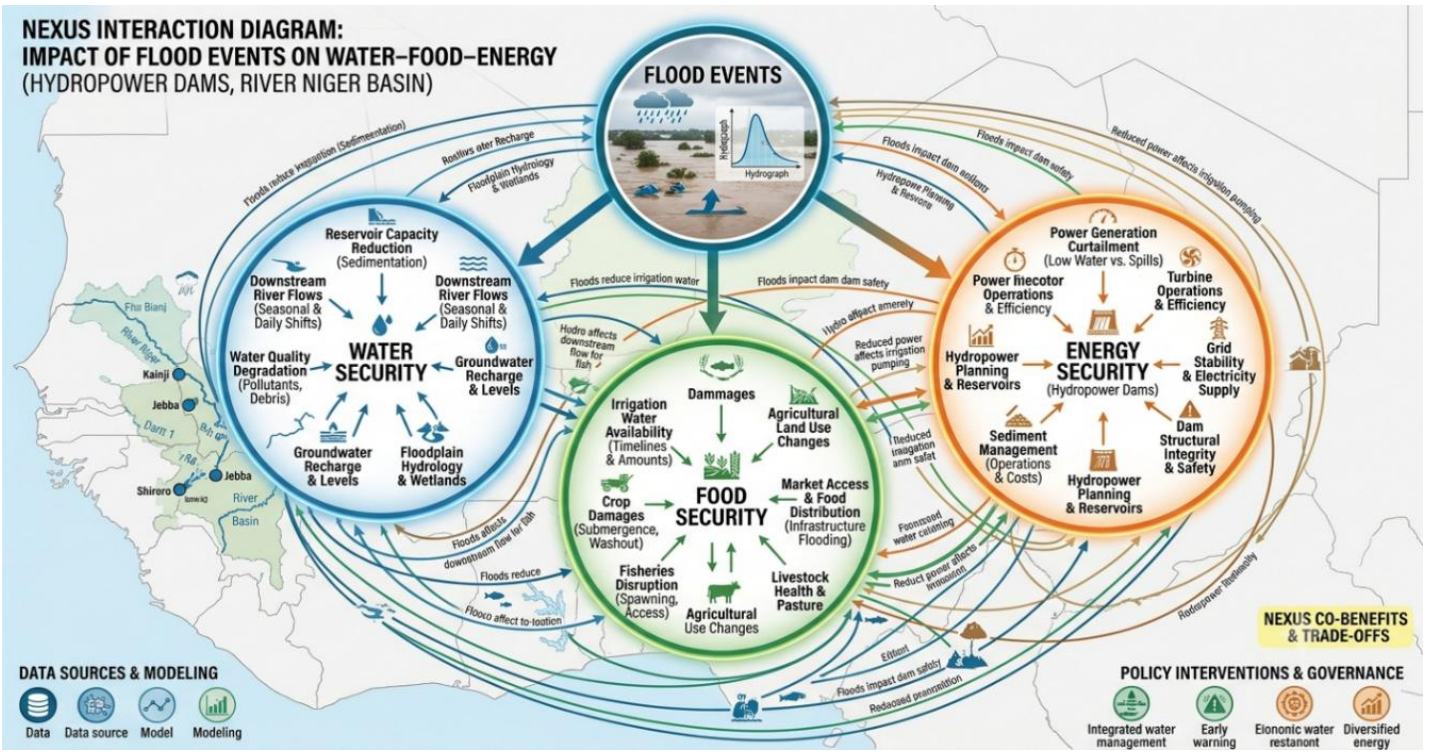


Fig. 4 Proposed Water–Food–Energy nexus framework showing flood event triggers, water security, food security, energy security dimensions, and policy interventions in the River Niger Basin. *Source: Original figure created by the authors*

The framework synthesizes the direct and indirect pathways through which flood events affect water availability and quality, food production systems, and hydropower generation, while illustrating cross-sectoral interactions, cascading failures, trade-offs, co-benefits, and opportunities for integrated flood management and climate-resilient governance.

6.2. Fisheries and Aquatic Food Systems

The Niger Basin's inland fisheries, particularly around Kainji Lake and the Inner Niger Delta, provide dietary protein and income for millions. During extreme floods, suspended sediment concentrations can exceed 3,500–4,000 mg L^{-1}, causing acute turbidity that suppresses primary productivity, clogs fish gills, and smothers benthic breeding habitats [29]. Rapid water level fluctuations associated with flood-control releases strand spawning grounds and disrupt lateral connectivity between the main channel and floodplain nursery habitats [22]. Post-flood studies in Kainji Lake have documented declines in artisanal catch per unit effort (CPUE) of 20–40% in the year following major sediment-laden flood events.

Furthermore, flood-induced eutrophication and algal blooms can trigger hypoxic conditions in reservoir bottom waters, causing fish kills and altering species composition toward less commercially valuable taxa. The loss of fisheries income compounds direct crop losses, deepening food insecurity among riparian communities that depend on mixed farming and fishing livelihoods.

6.3 Livestock and Pastoral Systems

Flood events associated with hydropower dam operations have significant implications for livestock production and pastoral livelihoods across the River Niger Basin. Livestock farming constitutes an important component of rural food

systems in many riparian communities, providing meat, milk, income, draft power, and socio-economic security. However, extreme flooding can disrupt these systems through multiple pathways, including pasture degradation, livestock displacement, disease outbreaks, water contamination, and economic losses.

One of the most immediate impacts of flooding is the inundation and destruction of grazing lands. Floodwaters can submerge pasture areas for prolonged periods, reducing forage availability and altering vegetation composition. In pastoral and agro-pastoral communities, flood-induced loss of dry-season grazing reserves forces herders to migrate in search of alternative feeding grounds. Such displacement often increases grazing pressure on available rangelands and may exacerbate conflicts between pastoralists and crop farmers over access to land and water resources [52]. In the Sahel and Niger Basin regions, the degradation of floodplain grazing ecosystems has been identified as a major threat to livestock productivity and pastoral resilience under changing hydroclimatic conditions.

Flood events also create favorable conditions for the emergence and transmission of livestock diseases. Stagnant floodwaters and waterlogged environments facilitate the proliferation of pathogens, parasites, and disease vectors, increasing the incidence of diseases such as leptospirosis, anthrax, foot rot, and vector-borne infections [49]. Contaminated drinking-water sources expose animals to gastrointestinal diseases and other health disorders, resulting in reduced productivity and increased mortality rates [53]. In addition, the destruction of veterinary infrastructure and restricted access to animal health services during flood emergencies can delay disease detection and treatment, further compounding livestock losses.

Although floods are often associated with increased water availability, they may simultaneously compromise water security for livestock. Floodwaters frequently transport sediments, agricultural chemicals, sewage, and other contaminants into rivers, reservoirs, and watering points. Consequently, livestock consuming contaminated water may experience reduced weight gain, lower milk production, reproductive challenges, and increased susceptibility to disease. These impacts highlight an important nexus interaction whereby flood-induced deterioration of water quality directly affects food production systems through livestock health and productivity.

Direct livestock mortality represents another major consequence of severe flooding. Animals may drown, become trapped in floodwaters, or suffer injuries during evacuation and relocation processes. Recent vulnerability assessments demonstrate that livestock mortality increases significantly with flood depth, flow velocity, and the speed of flood onset [54]. Historical flood events in Nigeria illustrate these risks; for example, the 2012 Lokoja flood reportedly resulted in the loss of more than 47,000 farm animals, causing substantial economic hardship for affected households.

The socio-economic consequences of livestock losses often extend beyond the immediate flood period. Reduced herd sizes, lower milk and meat production, declining reproductive performance, and disrupted market access can undermine household incomes and food security for extended periods. Furthermore, emergency spillway releases from major hydropower reservoirs such as Kainji and Jebba may inundate downstream grazing areas and livestock corridors, creating additional pressures on pastoral systems. These cascading impacts demonstrate that flood management in the River Niger Basin should not focus solely on protecting hydropower infrastructure but must also consider livestock-dependent livelihoods as an integral component of the water–food–energy nexus. Strengthening early warning systems, protecting floodplain grazing reserves, improving veterinary preparedness, and integrating pastoral concerns into reservoir operation strategies are therefore essential for enhancing resilience to future flood events.

6.4 Energy–Food Coupling: The Irrigation Processing Storage Chain

A frequently overlooked nexus pathway is the dependence of food systems on reliable electricity. Flood-induced hydropower curtailment at Kainji, Jebba, or Shiroro triggers grid instability that propagates into agriculture value chains:

- **Irrigation pumping:** Electric tube wells and surface pumps fail during blackouts, halting dry-season cultivation.
- **Cold storage:** Perishable produce (fish, vegetables, dairy) is lost when cold chains are interrupted.
- **Milling and processing:** Rice mills and flour processing facilities dependent on grid power face downtime, reducing post-harvest recovery.

This interdependence means a single flood event can destroy standing crops through inundation and cause post-harvest losses in storage due to power outages. These compound shocks to food security surpass the sum of individual sector impacts.

7. Flood Impacts on Energy Security

Energy security in the basin relies heavily on hydropower from the Kainji, Jebba, and Shiroro dams. These dams are very sensitive to changes in water levels. In wet years, they provide 25% to 30% of Nigeria's total on-grid generation, but this can drop to below 15% in dry years [55, 19]. Extreme flooding can lead to disastrous decisions. For example, on September 14, 1999, authorities opened the spillways at Kainji and Jebba [46, 56] to prevent the dams from collapsing due to heavy rainfall. Unfortunately, this resulted in devastating floods that killed over 1,000 people, submerged 1,500 houses, and left 52 primary schools uninhabitable [56]. Moreover, the long-term reliability of energy supply is threatened by sediment buildup in reservoirs. The Kiri Dam has lost 37% of its surface area between 1982 and 2025, reducing its ability to buffer floods and provide reliable irrigation [17]. Climate projections suggest that if emissions remain high, peak water flow at Kainji could decrease by 14%, potentially reducing annual hydropower generation by 17%. This represents a significant shortfall of 700 GWh, which is equivalent to the energy needs of 1.5 million households [57, 19].

7.1 Flood Impacts on Hydropower Output

Flooding completely changes how hydropower systems operate, forcing operators to prioritize flood control over electricity generation. During extreme inflows, spillway releases increase to maintain reservoir safety, reducing the volume of water available for turbine passage and potentially lowering effective hydraulic head [14, 58]. Hydropower generation is governed by the following relationship:

$$P_t = \eta \rho g Q_t H_t$$

Where:

- η = turbine-generator efficiency
- ρ = water density
- g = gravitational acceleration
- Q_t = turbine discharge
- H_t = net hydraulic head.

Flood-induced spill reduces Q_t and may alter H_t, thereby reducing P_t.

The rivers in the Niger Basin, Kainji, Jebba, and Shiroro, experience significant changes in water flow throughout the year. During peak rainy seasons, dam operators face critical operational decisions. Spillway releases to mitigate upstream flood risk inevitably curtail hydropower generation. Some studies have shown that doing this can lead to less efficient turbine operation and lower energy production, even when plenty of water is available. This phenomenon has been examined in detail by Aribisala and Sule [14] and Oyedepo [59]. Physical impacts further worsen output. High sediment loads and debris accelerate turbine abrasion, clog intake structures, and damage auxiliary electrical equipment, leading to forced outages or prolonged maintenance [60]. Climate-driven increases in flood magnitude and frequency are expected to intensify these risks. These vulnerabilities and operational trade-offs are systematically broken down in **Table 2.**

Table 2 Flood Impact Mechanisms and Energy Security Metrics

Flood Impact Mechanism	**Operational Effect**	**Affected Variable**	**Energy Metric Impacted**	**Expected Change**
Increased spillway discharge	Reduced turbine flow	$\downarrow Q_t$, $\downarrow H_t$	LOLE, EUE	Increase
Turbine shutdown	Unit unavailable	$\downarrow P_t$	LOLE	Increase
Turbine derating	Reduced MW capacity	$\downarrow P_t$	EAF	Decrease
Sediment & debris	Forced outages	↑ EOFH	EAF	Decrease
Flood damage to switchyard	Transmission constraint	↓ Effective dispatch	LOLE, SAIDI	Increase
Delayed recovery	Prolonged reduced output	$\downarrow P_t$	Resilience	Decrease

7.2. Grid Stability and Dispatch Constraints

Flood-induced disruptions in hydropower output interact directly with grid operations. In Nigeria's grid, where hydropower provides significant baseload, sudden reductions in generation increase stress on reserve margins and increase loss-of-load risk during peak consumption periods [61, 62]. Reduced hydropower output necessitates increased reliance on thermal generation, which may be constrained by fuel supply, ramping limitations, or elevated operating expenses [59, 63]. Hydrological forecasting uncertainty complicates power plant scheduling and dispatch decisions. To avoid flooding, power plants often take a cautious approach, which limits how much electricity they can produce. This can increase the risk of insufficient power when it is needed [64]. Flooding may also damage transmission infrastructure, including substations and transmission lines, particularly in flood-prone areas. Such damage can precipitate blackouts and further constrain electricity supply [65].

7.3 Structural and Mechanical Strains

Flood events generate sustained hydraulic loading on dam infrastructure. Elevated reservoir levels increase hydrostatic pressure against dam bodies and foundations, raising seepage gradients. Where drainage galleries are obstructed by sediment, pore pressure accumulation increases the risk of internal erosion [13]. Mechanical components experience intensified operational cycles: spillway gates undergo repeated actuation, intake screens accumulate debris, and turbine runners are exposed to sediment-laden flows. Sediment ingress accelerates blade abrasion and may induce cavitation during fluctuating head conditions [66]. Accumulated damage reduces equipment operational life and increases the probability of forced outages.

8. Nexus Interactions and Systemic Trade-offs

8.1. Conceptual Framework: Floods as WFE Stressors

Under baseline conditions, multi-purpose reservoirs generate synergies: stored water produces electricity, stabilizes irrigation releases, and buffers the domestic supply. Flood events, however, expose the structural tensions within this nexus. The same water mass that threatens dam safety forces spillway releases that inundate farmland while bypassing turbines. This section analyzes the interactions through synergies, trade-offs, and cascading failure pathways.

8.2. Synergies and Co-Benefits

Under conditions of moderate, predictable flooding, some benefits can result:

- **Sediment-borne fertility:** Controlled, planned flood releases deposit nutrient-rich sediments on floodplains. This enhances soil fertility, benefiting agriculture once floodwaters recede.
- **Refilling and storage:** High inflows replenish reservoir storage, increasing dry-season water and energy availability, provided sedimentation is effectively managed.
- **Fisheries productivity:** Seasonal flood pulses maintain hydrological connectivity, driving high-yield fisheries in the Inner Niger Delta and Kainji Lake.

These synergies depend on regulated, gradual flood routing. When extreme events overwhelm spillway capacity, the system shifts to an antagonistic operating mode.

8.3. Trade-offs and Sectoral Conflicts

The most acute trade-off is the safety–generation–irrigation trilemma. Dam operators must maximize spillway discharge to protect structural strength, which simultaneously:

1. Reduces hydraulic head and turbine discharge → lowers power output (Energy loss).
2. Increases downstream stage and velocity → inundates floodplain farms (Food/Water risk).
3. Stirs up sediment and pollutants, which can make the water quality worse, posing a risk to the water supply.

At Kainji and Jebba, spillway discharge during peak flood events can exceed 2,000 $m^3 \cdot s^{-1}$. This simultaneously constrains floodplain agricultural production and reduces hydropower generation by 20–35% [14, 59]. A second trade-off exists between sediment management strategies and sectoral outcomes. Flushing sediments (beneficial for water storage and energy efficiency) degrades downriver water quality and smothers irrigated fields. Conversely, trapping sediments preserves downstream clarity yet accelerates reservoir capacity loss, shortening future energy and irrigation reliability.

8.4. Cascading Failure Pathways

Flood impacts propagate through non-linear cascades that amplify total system vulnerability. Figure 5 illustrates how flood impacts propagate non-linearly through river–reservoir systems, transforming a single hydrologic extreme into compound failures across energy, water, food, and health sectors. Pathway A highlights a critical trade-off: during extreme rainfall, dam operators prioritize spillway releases to protect structural integrity, which forces turbine derating or shutdown. The resulting grid instability and blackouts then disable irrigation pumps and cold storage, directly causing post-harvest losses and dry-season crop failure. Pathway B captures a slower but equally pernicious cascade: watershed degradation delivers high sediment loads during floods, accelerating reservoir siltation and reducing active storage. That loss of buffer capacity diminishes dry-season releases, simultaneously constraining irrigation water (food), firm energy (power), and environmental flows (water quality/ecosystems). Pathway C introduces a

transboundary dimension: an emergency release from Lagdo Dam on the Benue River rapidly raises river stages, flooding unprotected Nigerian floodplains in Benue, Niger, and Kogi States. The resulting crop losses trigger food price spikes in distant urban markets, decoupling production shocks from consumption consequences. Pathway D adds a public health amplifier: flood-contaminated water elevates turbidity and pathogen loads, triggering cholera or diarrhea outbreaks. Agricultural labor incapacitation follows, reducing planting and harvesting capacity even in areas not physically damaged by floods. Together, these pathways demonstrate that flood vulnerability is not merely about inundation depth or duration, but about how infrastructure operation, sediment dynamics, transboundary governance, and health systems interact to create systemic risk. Effective mitigation, therefore, requires integrated reservoir management, watershed rehabilitation, coordinated transboundary protocols, and resilient water–health infrastructure, not isolated engineering fixes.

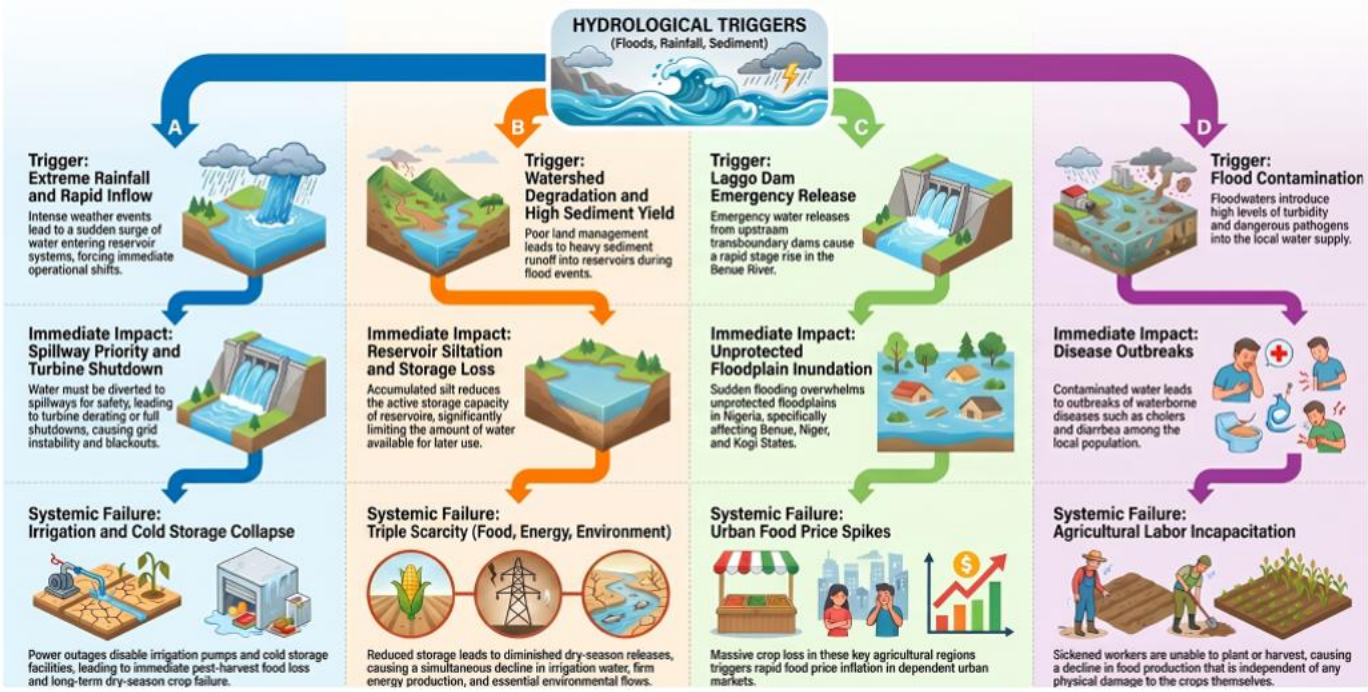


Fig. 5 The cascading pathways of hydrological collapse showing pathways A, B, C, and D for hydrological triggers, immediate impacts, and systemic failures. *Source: Original figure created by the authors*

8.5. Transboundary Dimensions

The Niger Basin presents a complex governance landscape for integrated water, environmental, and energy management. While the Niger Basin Authority (NBA) aims to coordinate water and environmental policies, energy and agricultural governance remains largely fragmented at the national level. This can cause problems during floods. For example, when the Lagdo Dam in Cameroon or the Selingue Dam in Mali releases water, it can help the upstream countries to generate more energy. However, such releases may induce downstream flooding in Nigeria, adversely affecting food systems. Critically, the absence of shared emergency protocols means that release decisions are made without comprehensive downstream information on agricultural status, water supply vulnerability, or available energy reserves. This information deficit can lead to suboptimal decisions that exacerbate downstream impacts. These transboundary governance challenges and information deficits create multi-sectoral trade-offs that affect regional resource management, as systematically synthesized in **Table 3**.

Table 3 Flood-induced impacts and trade-offs across the Water–Food–Energy nexus in the River Niger Basin.

Flood Impact Mechanism	Water Security	Food Security	Energy Security	Dominant Trade-off
Emergency spillway release	↓ Downstream water quality: ↑ contamination	↓ Floodplain crops; ↑ livestock displacement	↓ Turbine discharge; ↓ hydraulic head	Safety vs. Generation + Agriculture
Reservoir sedimentation	↓ Storage capacity; ↑ turbidity	↓ Irrigation reliability; ↓ fisheries yield	↓ Firm energy; ↑ turbine abrasion	Storage conservation vs. Flushing
Turbine shutdown/derating	—	↓ Irrigation pumping; ↓ cold storage	↓ Generation capacity; ↑ LOLE	Generation vs. Post-harvest preservation
Flood-induced grid instability	—	↓ Food processing; ↑ market disruption	↓ System frequency stability	Grid reliability vs. the agricultural industry
Wetland/floodplain degradation	↓ Natural filtration; ↓ baseflow	↓ Recession agriculture; ↓ fisheries	— (indirect via NBS loss)	Development vs. Ecosystem Services

Conclusion

This review demonstrates that floods at hydropower dams in the River Niger Basin impose compound impacts across water, food, and energy systems, underscoring the inadequacy of single-sector management approaches. Flood events make water unsafe to drink by introducing contaminants, allowing excessive algae growth, and stirring up sediment. This reduces reservoir storage capacity and increases water treatment costs for drinking and agricultural purposes. Food and energy security are compromised by both direct and indirect reactions. Floodplain agriculture and irrigation infrastructure sustain physical damage, while fisheries productivity declines due to ecosystem disruption. Hydropower operations are also limited by dam safety requirements, which require increased spillway discharge, reducing electricity generation. Sediment and debris additionally impair turbine performance, causing grid instability that disrupts cold chains, water pumping, and other energy-dependent food systems. The study also finds that dam operations involve structural trade-offs, in which managing safety, power generation, and irrigation often yields zero-sum outcomes across the water–food–energy nexus. These problems are exacerbated by the absence of integrated operational systems and transboundary governance, which allow upstream flood management decisions to impose high downstream costs. Addressing flood risks in the River Niger Basin necessitates coordinated, basin-wide, and nexus-informed governance to enhance resilience and sustainability.

Recommendations

To address these challenges, rules for managing reservoirs that account for the connections among water, food, and energy must be put in place. These rules should incorporate agricultural calendars and downstream water quality

criteria into spillway operation decisions. Establishing multi-sectoral early warning systems that integrate hydrological, agricultural, and energy data is essential for coordinated flood risk response.

The paper also advocates for expanding nature-based solutions at the catchment scale to reduce flood intensity and sediment loads before they reach reservoirs, thereby enhancing dam performance and resilience. Additionally, it calls for developing transboundary WFE emergency protocols under the Niger Basin Authority (NBA) to ensure coordinated spillway operations and downstream preparedness across water, food, and energy sectors. Safeguarding hydropower in the Niger Basin requires recognizing that dams serve as nexus infrastructure, not merely as energy assets. Their management directly affects the security of water, food, and energy for over 100 million people.

Author Contributions

Adelaja, A. R.: Methodology, Writing- Original Draft Preparation, **Writing-** Review & Editing; **Ahmed, K.:** Conceptualization, Writing- Original Draft Preparation, Writing- Review & Editing. **Eletta, O. A. A.:** Writing– Review & Editing, Supervision. **Olorunleke, A.:** Writing- Original Draft Preparation. **Ita, D. E.:** Writing – Original Draft Preparation. **Abdullahi, M.:** Supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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