

A Study on the Water-Energy-Food-Ecosystem (WEFE) Nexus in the Niger-Benue River System, Nigeria

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Front cover photo: A water reservoir for small-scale irrigation at Ibadan, Nigeria (*photo*: Birhanu Zemadim/IWMI)

Back cover photo: A small-scale irrigation setup for rice at Ibadan, Nigeria (*photo*: Birhanu Zemadim/IWMI)

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Acronyms and Abbreviations

AGB	Above-ground biomass
AHP	Analytic Hierarchy Process
BCM	Billion cubic metres
BGS	British Geological Survey
DIWASA	Digital Innovations for Water-Secure Africa
ECN	Energy Commission of Nigeria
ESA	European Space Agency
ESDAC	European Soil Data Centre
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FB	Fuel biomass
FCT	Federal Capital Territory
GAEZ	Global Agro-Ecological Zones
GEE	Google Earth Engine
GIS	Geographic Information System
GloSEM	Global Soil Erosion Modelling platform
GLWD	Global Lakes and Wetlands Database
GWh	Gigawatt-hour
GWS	Groundwater storage
HA / HAs	Hydrological Area(s)
HP	Hydropower
ICS	Improved cookstove
IIASA	International Institute for Applied Systems Analysis
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature
KgDM	Kilograms of dry matter
LS	Slope length and steepness factor (RUSLE)
LTA	Long-term average
LULC	Land use and land cover
MOD44W	MODIS Land Water Mask product
MODIS	Moderate Resolution Imaging Spectroradiometer
MW	Megawatt
NERCEDs	Natural Environment Research Council, Environmental Data Service
PET	Potential evapotranspiration
PV	Solar photovoltaic
Qsurf	Surface runoff volume
RBDA	River Basin Development Authority

RUSLE	Revised Universal Soil Loss Equation
SER	Sediment enrichment ratio
SSA	Sub-Saharan Africa
SSC	Suspended sediment concentration
SSEB	Simplified Surface Energy Balance
SY	Sediment yield
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WDPA	World Database on Protected Areas
WEFE	Water-Energy-Food-Ecosystem
WELF	Water, Energy, Land and Food (nexus)

Summary

The Niger–Benue River System is one of Nigeria's most strategic hydrological networks, supporting irrigation, hydropower generation, fisheries, urban water supply, and critical ecosystem services. However, the basin faces increasing pressure from unregulated water abstraction, seasonal flooding, dry-season water scarcity, pollution, land degradation, and fragmented institutions, making integrated resource planning essential. This study applies the Water–Energy–Food–Ecosystem (WEFE) Nexus framework to assess spatial patterns, interdependencies, and opportunities across four major hydrological areas: Niger North, Niger Central, Upper Benue, and Lower Benue.

Using a mixed-methods approach that combines systems analysis, Geographic Information Systems, and open-source remote sensing datasets, the study maps and quantifies key WEFE indicators, including land use and land cover, surface runoff, groundwater storage, hydropower, solar and biomass energy potential, irrigated agricultural productivity, protected and wetland areas, evapotranspiration, and soil erosion risk. The analysis draws on spatial datasets such as the 2024 Environmental Systems Research Institute (ESRI) land cover data, Digital Innovations for Water-Secure Africa (DIWASA) discharge estimates, groundwater storage data, Global Agro-Ecological Zones (GAEZ) agricultural indicators, World Database on Protected Areas (WDPA) and ecosystem datasets from the Global Lakes and Wetlands Database (GLWD) and Revised Universal Soil Loss Equation (RUSLE) based erosion estimates.

The findings show that WEFE resources are abundant but unevenly distributed across the river system. Upper Benue emerges as the main runoff engine, generating the highest surface water volume, while Niger North holds the largest groundwater storage, making it important for dry-season agricultural resilience. Niger Central dominates existing hydropower generation and records the highest total agricultural production, while Upper Benue shows the strongest untapped potential for solar and biomass energy development. In contrast, Lower Benue, despite its smaller area, faces the highest erosion burden and the lowest protected-area coverage, indicating significant ecosystem vulnerability.

Overall, the study demonstrates that the Niger–Benue River System cannot be managed effectively through sector-specific or uniform interventions. Instead, basin-specific strategies are needed to balance hydrological potential, energy development, food production, and ecosystem protection. The results highlight the importance of coordinated governance, data-driven planning, and targeted investments in renewable energy, irrigation efficiency, wetland conservation, and erosion control. Strengthening ecosystem resilience is therefore not only an environmental priority but also a foundation for sustaining water, energy, and food security within Nigeria's broader development agenda.

1. Introduction

The Water–Energy–Food–Ecosystem (WEFE) Nexus has emerged as a central framework for addressing the growing interdependencies among critical resource systems. Early work emphasized interconnections among water, energy, and food systems (Ringler et al. 2013; Bazilian et al. 2011). Subsequent studies expanded the framework to include ecosystems, highlighting their essential role in sustainable natural resources management (Biggs et al. 2015). Ecosystem services such as water regulation, soil fertility, and biodiversity conservation are essential to long-term sustainability, yet policy and planning processes often undervalue them. Recent studies have focused on operationalizing the nexus, moving beyond conceptual discussions toward practical implementation strategies. Endo et al. (2017) noted that while the nexus concept is widely accepted, its application remains limited due to methodological challenges, data constraints, and institutional fragmentation. Similarly, Simpson and Jewitt (2019) argue that translating nexus thinking into policy and practice requires robust analytical tools, stakeholder engagement, and governance mechanisms that facilitate cross-sectoral coordination.

In river basins, the nexus approach is particularly relevant because of the spatial and functional interconnections among water, energy, food, and ecosystem services. River basins serve as natural units for integrated resource management, providing a platform for analyzing trade-offs and synergies across sectors. Studies have shown that basin-scale interventions, such as multi-purpose reservoir management and integrated irrigation-energy systems, can significantly enhance resource-use efficiency and resilience (Daher and Mohtar 2015). In sub-Saharan Africa, the WEFE Nexus is gaining attention due to the region's vulnerability to climate change and resource constraints.

Rapid population growth and economic development are driving increased demand for water, energy, and food, while climate variability exacerbates resource scarcity and environmental degradation (Conway et al. 2017). In this context, the nexus approach offers a framework for balancing competing demands and promoting sustainable development. In complex river basins such as the Niger–Benue system, numerous studies highlight the potential of integrated approaches within the WEFE nexus. However, data on key WEFE indicators remain insufficiently addressed. This study therefore fills this gap by applying a systems-based spatial analysis to identify, map, and quantify WEFE-Nexus indicators and assess their spatial distribution across the Niger–Benue river system.

2. Methodology

2.1 System Boundaries and Nexus Scope

The study area is the Niger–Benue River system, formed by the confluence of the Niger and Benue rivers at Lokoja, Nigeria (Figure 1). The river system is strategic for irrigated agriculture, hydropower, fisheries, urban water supply, and ecosystem services. Yet it faces unregulated upstream water abstraction, flooding, dry-season scarcity, pollution, land degradation, and institutional fragmentation. The river system spans diverse ecological zones and features key infrastructure, such as the Kainji, Jebba, Shiroro, and Zungeru hydropower dams.

The Niger-Benue River System covers five hydrological areas, HA-1 to HA-5. HA-5 largely covers the Niger Delta, an oil-producing region. HA-1 to HA-4 cover 20 states and the Federal Capital Territory (FCT). Therefore, this study is limited to four hydrological areas: Niger North (HA-1), Niger Central (HA-2), Upper Benue (HA-3), and Lower Benue (HA-4). Table 1 presents the full list of Nigerian Hydrological Areas (HAs), along with drainage areas, River Basin Development Authorities (RBDAs), and the states covered by RBDAs within the HAs.



Figure 1. The Niger-Benue River System in Nigeria

Source: Authors' data

Table 1. Nigeria Water Resources Hydrological River Basin Delineation

Hydrological Area (HA)	Drainage Area (km ²)	River Basin Development Authority (RBDA)	State coverage by RBDAs in HAs
Niger North (HA-1)	131,600	Sokoto Rima	Sokoto, Kebbi, Zamfara and Katsina
Niger North (HA-1)	131,600	Upper Niger	Niger (part)
Niger North (HA-1)	131,600	Hadejia Jama'are	Kano (part)
Niger Central (HA-2)	158,100	Upper Niger	Niger, Kaduna, and FCT
Niger Central (HA-2)	158,100	Lower Niger	Kwara and Kogi (part)
Niger Central (HA-2)	158,100	Sokoto Rima	Katsina (part) and Zamfara (part)
Niger Central (HA-2)	158,100	Ogun Oshun	Oyo (part)
Niger Central (HA-2)	158,100	Benin Owena	Ekiti (part)
Niger Central (HA-2)	158,100	Lower Benue	Plateau (part)
Upper Benue (HA-3)	158,900	Upper Benue	Adamawa, Gombe, Taraba, Bauchi (part)
Upper Benue (HA-3)	158,900	Lower Benue	Plateau (part), and Benue (part)
Upper Benue (HA-3)	158,900	Chad Basin	Yobe (part), Borno (part)
Lower Benue (HA-4)	73,000	Lower Benue	Benue (part), Nasarawa, Plateau (part), Kogi (part)
Lower Benue (HA-4)	73,000	Upper Niger	Kaduna (part), and FCT (part)
Lower Benue (HA-4)	73,000	Upper Benue	Taraba (part)
Lower Benue (HA-4)	73,000	Cross River Basin	Cross River (part)
Niger South (HA-5)	53,900	Niger Delta Basin	Rivers (part), Bayelsa, Delta (part)
Niger South (HA-5)	53,900	Anambra Imo	Anambra, Imo (part), Enugu (part)
Niger South (HA-5)	53,900	Benin Owena	Edo (part)
Niger South (HA-5)	53,900	Lower Benue	Kogi (part)
Western Littoral (HA-6)	100,500	Ogun Oshun	Ogun, Oyo, Oshun, and Lagos
Western Littoral (HA-6)	100,500	Benin Owena	Ekiti (part), Ondo, Edo (part) and Delta (part)
Western Littoral (HA-6)	100,500	Lower Niger	Kwara (part) and Kogi (part)
Eastern Littoral (HA-7)	59,800	Anambra Imo	Ebonyi, Abia, Imo (part), Enugu (part)
Eastern Littoral (HA-7)	59,800	Cross River	Cross River, Akwa Ibom
Eastern Littoral (HA-7)	59,800	Niger Delta	Rivers (part)
Eastern Littoral (HA-7)	59,800	Lower Benue	Benue (part)
Chad Basin (HA-8)	188,000	Chad Basin	Borno (part), Yobe (part)
Chad Basin (HA-8)	188,000	Hadejia Jama'are	Kano, Jigawa and Bauchi (part)
Chad Basin (HA-8)	188,000	Lower Benue	Plateau (part)
Chad Basin (HA-8)	188,000	Sokoto Rima	Katsina (part)
Chad Basin (HA-8)	188,000	Upper Niger	Kaduna (part)

Source: Irrigation in Nigeria (Handbook) (Federal Ministry of Water Resources 2021)

2.2 WEFE-Nexus Indicators and Spatial Assessment

We used Geographic Information System (GIS) software and open-source remote sensing data in Google Earth Engine (Gorelick et al. 2017) to map and analyze spatial patterns of WEFE indicators across the hydrological areas in the Niger-Benue River system. We started with land-use and land-cover classification for each hydrological area, followed by spatial analysis of (i) water availability, (ii) energy sources, (iii) food system, and (iv) ecosystem assessment.

2.2.1 Land use and land cover classification

We used the 2024 ESRI 10-meter Land Use and Land Cover (LULC) data. The dataset is a high-resolution product distributed freely under a Creative Commons license and is based on Sentinel-2 satellite imagery from the European Space Agency (ESA) (Kerner et al. 2024). The land cover classes are aligned with the UN-FAO Land Cover Classification System (Zanaga et al. 2021).

2.2.2 Water availability

The indicators assessed to diagnose the water domain include quantifying the surface runoff volume and groundwater storage within the hydrological areas. Surface runoff volume data were sourced from the IWMI-based AfriDischarge v1 dataset (Akpoti et al. 2024a). The dataset provides monthly river discharge estimates across Africa at a 1 km spatial resolution, covering more than 650,000 river segments (Akpoti et al. 2024a). We derived groundwater storage volume (GWS_vol) from the British Geological Survey (BGS) Groundwater Resources of Africa dataset (MacDonald et al. 2012). The spatial estimates were validated against reported hydrological datasets in the Niger-Benue River system (Afolabi 2025; Merem et al. 2017).

Surface runoff volume (Qsurf): To estimate the annual surface runoff volume (Qsurf_vol), a pixel area was used to determine the volumetric contribution of surface runoff, as given by equation 1.

$$V_{pixel}(km^3) = D_i(mm) \times A_{pixel}(km^2) \times 10^{-6} \quad (Eq1)$$

Where D_i represents the runoff depth at pixel i obtained from AfriDischarge v1 hydrological dataset, and the factor 10^{-6} serves as a unit conversion from $mm \cdot km^2$ to km^3 . The monthly volumes were then summed across all pixels within each basin, and the annual Qsurf_vol was obtained by aggregating the twelve-monthly volumetric estimates using equation 2.

$$Qsurf_{vol}(km^3) = \sum Qsurf_{vol,m} \quad m = 1, 2, \dots, 12 \quad (Eq2)$$

Groundwater storage (GWS): Groundwater storage was derived from the British Geological Survey Groundwater Resources of Africa Dataset (MacDonald et al. 2012). The dataset defines groundwater storage as the saturated aquifer thickness multiplied by the effective porosity. This is a storage volume expressed per unit area, that is, a storage depth. It differs from the depth to the water table (MacDonald et al. 2012). The dataset classifies this storage into six classes. Each class was assigned a representative midpoint depth in millimeters. The No storage class was set to 0 mm. The Low class was set to 500 mm. The Low to Medium class was set to 5,000 mm. The Medium class was set to 17,500 mm. The High class was set to 37,500 mm. The Very High class was set to 60,000 mm. This produced a continuous

storage depth raster across the study area. The raster was resampled to 1 km resolution using bilinear interpolation and then spatially smoothed. Open water pixels were removed using the MODIS MOD44W water mask. This mask was aggregated from 2000 to 2015 to capture both permanent and seasonal water bodies.

$$GWS_{vol}(km^3) = GWS(mm) \times A_{pixel}(km^2) \times 10^{-6} \quad (Eq3)$$

Where GWS is the spatial mean storage depth across the basin, A is the basin area in km², and the factor 10⁻⁶ accounts for the unit conversion from mm·km² to km³.

2.2.3 Energy sources

The study assessed hydropower production areas and opportunities for solar-powered energy systems. The study estimated other energy sources (wood biomass) using land-use and land-cover suitability maps.

Hydropower Generation and Water Used

Annual hydropower statistics were sourced from the Energy Commission of Nigeria (ECN) Statistical Databank available at <https://databank.energy.gov.ng>. We retrieved records of electricity generation and water used for generation, with available data spanning 1969 to 2022. Plant-level annual generation and water use figures were computed as arithmetic means, excluding missing observations, and HA-level summaries were derived as equally weighted averages of the contributing plant estimates.

Solar PV Site Suitability and Energy Potential

Solar photovoltaic (PV) site suitability across Nigeria was assessed by combining GIS analysis with the Analytic Hierarchy Process (AHP) in Google Earth Engine, using the long-term average global solar atlas dataset (ESMAP, 2019) and 2020 land cover. A hard constraint mask first removed pixels that were legally, ecologically, or physically unsuitable, namely permanent water, wetlands, cropland and built-up areas, protected areas (Zanaga et al. 2021; UNEP-WCMC and IUCN, 2024), and slopes above 5° (USGS SRTM). The remaining pixels were scored with a five-criterion weighted overlay combining photovoltaic output (0.45), transmission proximity (0.25), slope (0.15), road proximity (0.10), and aspect (0.05), with weights derived by AHP (CR ~ 0.063). The resulting 0 to 1 scores were classified as High (= 0.75), Moderate (0.50 to 0.75), and Low (< 0.50), and aggregated across the eight hydrological assessment basins (HA-1 to HA-8) as mean score and suitable area per basin.

Fuel Biomass and Energy Potential

Fuel Biomass (FB) data were derived from the ESA Climate Change Initiative v7.0 above-ground biomass (AGB) product (Santoro and Cartus 2026) at 100 m resolution using Google Earth Engine. The available fuel biomass was estimated by applying biome-stratified extraction fractions to the AGB standing stock, with values assigned by land cover class using ESA WorldCover 2021: tree cover (0.35), shrubland (0.25), grassland (0.10), cropland residues (0.15), and zero for water bodies, built-up areas, and mangroves. Energy potential under an improved cookstove (ICS) scenario — the primary indicator used in the WEFE Nexus analysis — was then computed. Results were aggregated by hydrological areas. As biomass extraction is restricted in the protected areas, its potential was excluded by applying the World Database on Protected Areas (WDPA) mask.

2.2.4 Food systems assessment

The food systems assessment incorporated spatial predictions of agricultural water withdrawals, irrigated crop yield, crop biomass, and total crop production, all presented per hydrological area. Data were extracted from the Global Agro-Ecological Zones (GAEZ) database compiled by the Food and Agriculture Organization of the United Nations and the International Institute for Applied Systems Analysis (FAO and IIASA 2025).

In Nigeria, agriculture accounts for about 44% of total water withdrawal, supporting irrigation for crops such as maize, cassava, and rice, as well as livestock and fisheries. Municipal/domestic water withdrawal accounts for 40%, and industry accounts for approximately 16% of total water withdrawal (Johnson 2026). Data on irrigated crop yield, biomass, and total production represent the average attainable yield, biomass, and production of the best-occurring suitability class per grid cell over the 2001–2020 baseline period. The GAEZ v5 R package returns values in their final published units, so no additional scale factor was applied, and data were computed per hydrological area (FAO and IIASA 2025).

2.2.5 Ecosystem assessment

The ecosystem assessment included delineating and quantifying protected and wetland areas and estimating soil erosion losses for each hydrological area. Area boundaries were sourced from the World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN 2024) and the Global Lakes and Wetlands Database (GLWD) (Lehner et al. 2025). Datasets were accessed through the Google Earth Engine (GEE) data catalog and filtered to retain only polygons falling within Nigeria's national boundary.

Evapotranspiration Estimation

Annual actual evapotranspiration within protected areas and wetlands, and croplands under irrigated and rainfed conditions were estimated using the Simplified Surface Energy Balance (SSEB) model. The model is a satellite-driven ET product developed by the United States Geological Survey (USGS) that derives actual ET by combining MODIS land surface temperature with gridded reference ET (Senay et al. 2023).

Evaporation from hydropower reservoirs was estimated separately as potential evapotranspiration, using the open-water evaporative demand. Reservoir surface areas (Global Dam Watch; Lehner et al. 2024) were multiplied by the TerraClimate long-term mean PET depth for 2000 to 2024 (Abatzoglou et al. 2018). The resulting annual volumes were summed within each hydrological area.

Soil Erosion: Annual soil erosion was obtained from the Global Soil Erosion Modeling platform (GloSEM), distributed by ESDAC (Borrelli et al. 2022), which applies the Revised Universal Soil Loss Equation (Eq4):

$$\text{Annual Soil Erosion } \left(\frac{\text{ha}}{\text{yr}} \right) = R \times K \times LS \times C \times P \quad (\text{Eq4})$$

Where R is rainfall erosivity, K is soil erodibility computed as a percentage of soil texture (sand, silt, and clay) using the ISRIC dataset available at (<https://data.isric.org>), LS is slope length and steepness, C is cover management, and P is support practice. The raster was

clipped to Nigeria's eight Hydrological Areas and resampled to a 1 km grid. Sanogo et al (2023) presented the full methodology for the computation of R, K, LS, C, and P.

Suspended Sediment Concentration: Suspended sediment concentration (SSC) in agricultural overland flow was computed from delivered sediment and annual surface runoff from VegDischarge v2 (Akpoti et al. 2024b) using equation 5, consistent with Section 2.2.2. Basin values are reported as the mean SSC across cropland pixels, while the total SSC within each hydrological area was calculated by summing SSC values across all land-use types.

$$SSC \left(\frac{g}{L} \right) = (SY \times 10^6 \times SER) / (Q_{surf} \times 10^4) \quad (Eq5)$$

Where SSC is suspended sediment concentration in mg/L, SY is the delivered sediment yield ($t \text{ ha}^{-1} \text{ yr}^{-1}$), obtained as the product of the RUSLE soil loss rate and a connectivity-based sediment delivery ratio derived following Vigiak et al. (2012); Qsurf is the annual surface runoff depth (mm); 10^6 converts tonnes to grams; and 10^4 converts mm over one hectare to liters. A sediment enrichment ratio (SER) of 3.0 accounts for preferential entrainment of fine fractions by overland flow (2.0–5.0) for tropical soils as per Kinnell (2010).

3. Results

3.1 Land Use and Land Cover Classification

Figure 2 presents Nigeria's land-use and land-cover data, derived from the 2024 ESRI database. Approximately 57% of Nigeria's water bodies are located within the four hydrological areas (HA-1 to HA-4) of the Niger–Benue River System. These hydrological areas also account for 78% of the country's cropland. The land use system in the Niger–Benue River System is dominated by grass/shrub cover, and two hydrological areas (HA-2 and HA-3) in the Niger–Benue show particularly large forest extents (35%). Water bodies and flooded vegetation occupy relatively smaller proportions across all the hydrological areas of the Niger–Benue river system. Built-up and bare ground areas also remain minimal compared to other land cover types, though HA-2 and HA-4 show slightly higher built-up expansion than the others.

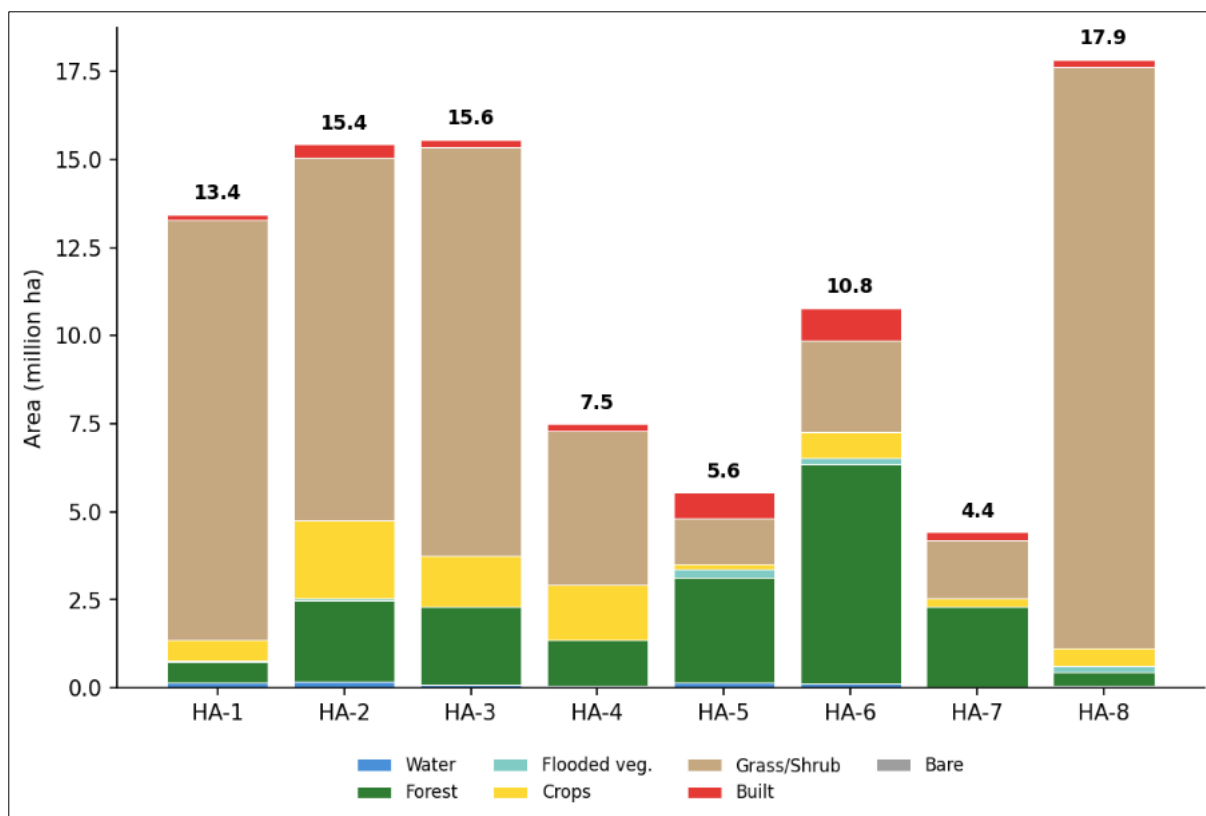


Figure 2. Land use and land cover map of Nigeria – 2024

Source: Authors' data

3.2 Water Availability

Figure 3 presents surface water potential (Qsurf), and groundwater storage (QGWS) across eight major Hydrological Areas (HA-1 through HA-8). Focusing on the Niger-Benue River system (HA-1 through HA-4), Upper Benue (HA-3) is the runoff engine. Despite being similar in size to HA-2, the Upper Benue generates the most surface water by a significant margin 67 billion cubic meters (BCM). The Lower Benue (HA-4) has the smallest area, yet yields roughly double the surface water per square kilometer of the Niger Basin (HA-1), indicating intense runoff and likely higher precipitation or steeper gradients. The Niger Central (HA-2) provides a massive surface runoff volume of 58.8 BCM, functioning as the main stabilizing volume for the Niger side of the confluence. The Niger Basin (HA-1) holds the most groundwater volume (18.91 BCM), suggesting a highly permeable geology where water infiltrates rather than runs off, making it a vital buffer for crop water use during dry seasons. In contrast, Niger Central (HA-2) generates massive surface water but retains only 9.74 BCM in groundwater storage. The Upper Benue (HA-3) has the highest surface water (67 BCM) and the second-highest groundwater storage (16.01 BCM), making it arguably the most resource-rich and hydrologically active zone.

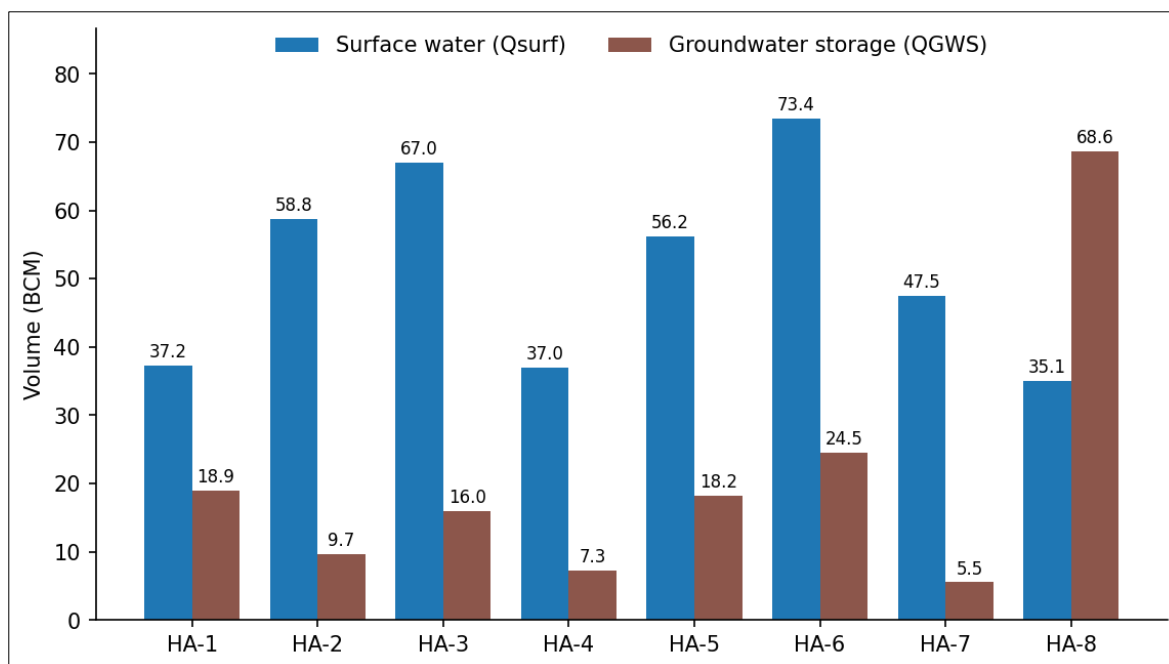


Figure 3. Surface runoff and groundwater storage volumes in Niger-Benue River systems.
Source: Authors' data

3.3 Energy Availability

Hydropower

Nigeria's hydropower infrastructure centers on four major facilities: Kainji, Jebba, Shiroro, and Zungeru (Figure 1; Table 2). The Kainji Dam, located in the Niger North hydrological area (HA-1), has an installed capacity of 760 MW and utilizes approximately 27.56 billion cubic meters (BCM) of water annually (Adegbehin et al. 2016). Downstream, the Jebba Dam contributes 578 MW, with an annual water use of about 12.1 BCM. Jebba's reservoir inflow exceeded Kainji's outflow during 1986–2020, averaging about 40.6 BCM/year at Jebba versus 33.7 BCM/year at Kainji—an estimated difference of about 7 BCM/year. This difference is consistent with additional inflows from the intervening catchment between the two reservoirs. Jebba water inflow is higher and generates more electricity than Kainji, despite having a smaller installed capacity.

The Shiroro Dam, situated in Niger Central (HA-2), has a generation capacity of 600 MW and receives an annual inflow of approximately 22.9 BCM (Amogu 2022). Table 2 shows the reservoir area and evaporative water demand for these hydropower reservoirs. The Zungeru Hydropower Dam, a more recent addition, became fully operational in 2023 and has a capacity of 700 MW, with an estimated annual water use of 39.4 BCM. Basin-wise analysis indicates that Niger Central (HA-2) is the leading hydropower-producing region, generating approximately 16,451 GWh per year from major dams such as Jebba, Shiroro, and Zungeru. The Niger North also contributes substantially, producing about 6,657.6 GWh annually, largely driven by the Kainji Dam. However, data on hydropower generation and water use in the Upper and Lower Benue hydrological areas (HA-3 and HA-4) are notably lacking (Table 2).

Solar Power Potential

Solar photovoltaic suitability of Nigeria is presented in Figure 4 and Table 2. Within the Niger-Benue River system, the Upper Benue hydrological area (HA-3) has the highest potential land area for solar power (49,186.5 hectares), followed closely by Niger Central. The Niger Basin has the least solar potential (13,228.3 hectares). According to The Business Times (Nigeria), by the end of 2025, Nigeria's cumulative installed solar PV capacity had reached approximately 1,190 MW — still less than 2% of the country's overall energy mix. With an estimated 134,000 hectares of land suitable for solar PV development across the four hydrological areas (HA1-HA4), Nigeria has substantial untapped potential for solar expansion, particularly in off-grid regions.

Biomass Potential

The sustainable fuel biomass energy potential of Nigeria is presented in Figure 4 and Table 2. Within the Niger-Benue River system, the Upper Benue hydrological area (HA-3) leads heavily in biomass potential, generating 72.1 million GJ of total biomass energy. Niger Central (HA-2) is a close second with 65.4 million GJ. In stark contrast, the Niger Basin (HA-1) has a significantly lower biomass energy potential (approx. 4.5 million GJ). Lower Benue, despite having the smallest area, has the highest area-normalized (GJ/km²) biomass energy potential of all four HAs (Figure 4).

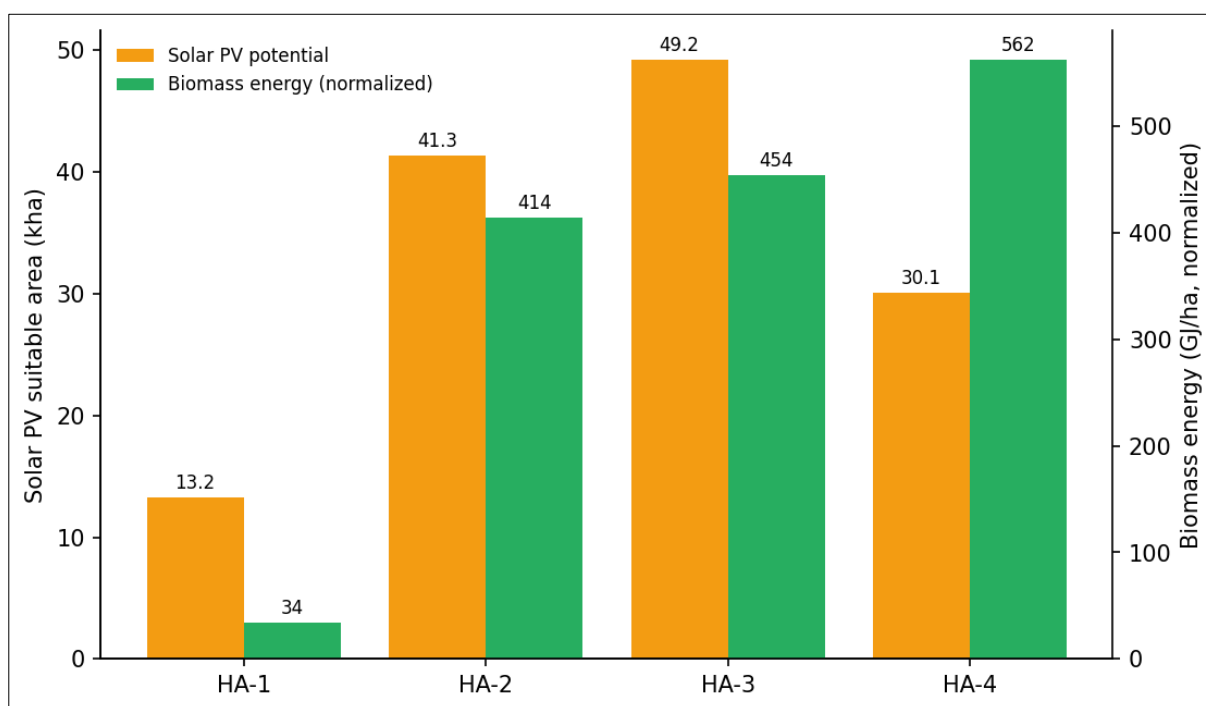


Figure 4. Solar Photovoltaic and Biomass Suitability of Nigeria

Source: Authors' data

Table 2. Energy availability in the different hydrological areas

Basin	Area (km ²)	Hydropower Generation (GWh/yr)	Water used (BCM) and Reservoir Surface Area (Km ²)	Evaporative Demand from HP Reservoirs (BCM)	Solar PV Potential (ha)	Biomass (t)	Biomass Energy (GJ Total)	Biomass Energy (GJ Total) Area Normalized (GJ/km ²)
Niger Basin (HA-1)	131,600	6,657.6	27.56/1035 (Kainji)	1.79 (Kainji)	13,228.30	1,504,109	4,521,728	34.36
Niger Central (HA-2)	158,100	16,451	Jebba (12.1/275), Shiroro (22.9/271), Zungeru (39.4)	0.442 (Jebba) 0.462 (Shiroro)	41,342.33	21,700,000	65,400,000	413.66
Upper Benue (HA-3)	158,900	ND*	ND	ND	49,186.50	24,000,000	72,100,000	453.74
Lower Benue (HA-4)	73,000	ND	ND	ND	30,056.23	13,700,000	41,000,000	561.64

Note: *ND – No Data

Source: Authors' data

3.4 Food Systems Assessment

According to Johnson (2026), agricultural water withdrawal in Nigeria—comprising irrigation, livestock, and pond aquaculture—amounts to about 5.5 billion cubic meters (BCM) per year, roughly 44% of the country's total annual freshwater withdrawal. Table 3 and Figure 5 present the agricultural potential of four hydrological areas under irrigated conditions. Key insights are as follows:

- **Geographic Area & Total Production:** Niger Central (HA-2) produces the highest total agricultural output at 2,117,968.06 tons/yr. The Lower Benue (HA-4) is less than half the size of the other basins and correspondingly has the lowest total production (1,117,716.2 tons/yr).
- **Irrigation Development:** Irrigation development in the Niger–Benue River System is concentrated in Niger North (HA-1), Niger Central (HA-2), Upper Benue (HA-3), and Lower Benue (HA-4) (Figure 5). These hydrological areas contain 182 formal irrigation dams: 61 large, 92 medium, and 29 small dams (Table 3). Although medium dams are the most numerous, large dams account for most irrigable land and remain central to national irrigation development and food production. The combined potential irrigable area associated with these dams is about 373,228 ha. Large dams account for 84.9% of this potential, while medium and small dams contribute 3.2% and 0.2%, respectively.
- **Irrigated Areas versus the Potential:** Only about 44,145 hectares have been developed, representing 11.8% of the estimated potential. Large dams account for most of the developed areas, followed by medium and small dams. This gap shows substantial scope to rehabilitate, expand, and modernize existing schemes.

- Actual cultivation is much lower. About 18,981 ha are actively cropped, equivalent to 43% of the developed area and roughly 5% of total irrigation potential. This underperformance reflects poor maintenance, unreliable water delivery, deteriorating infrastructure, limited funding, weak institutions, and low farmer participation.
- Large versus Small Scale Irrigation: Formal irrigation schemes support about 24,261 farming households. Large schemes serve 61.4% of farmers, medium schemes 34.8%, and small schemes 4.0%. This confirms the importance of large public schemes while also highlighting the role of medium-scale systems in local food production and rural employment. Average farm sizes remain small, ranging from 0.5 to 0.75 ha in large and medium schemes and from 0.25 to 0.50 ha in small-dam schemes. Formal irrigation therefore mainly serves smallholders. While small plots widen participation, they may limit mechanization, commercial scaling, and economies of scale.
- Performance varies across hydrological areas: HA-3 has the largest irrigation potential, followed by HA-1, HA-4, and HA-2. However, HA-4 has the largest developed irrigation area, suggesting comparatively greater implementation. HA-3 supports the most irrigation farmers, reflecting its water resources and agricultural importance within the Benue Basin. The Niger–Benue River System has substantial but underused formal irrigation potential (326,268 ha). Of this, about 44,145 ha (13%) have been developed, and about 18,041 ha (40%) of the developed area is actually cropped (Figure 5). Large dams dominate irrigable land and storage capacity, but most farmers cultivate small plots within public schemes. Improving scheme performance will require rehabilitation, stronger operation and maintenance, farmer support services, modern water delivery, solar-powered pumping, pressurized irrigation, and digital water management.
- Crop and Biomass Yield: The Niger North (HA-1) has the highest potential Irrigated Crop Yield (8,856.3 Kg/ha/yr) and the highest potential Irrigated Biomass Yield (11,024.1 KgDM/ha/yr). Relatively, the Lower Benue (HA-4) has the lowest potential yields per hectare for both crop (7,064.8 kg/ha/yr) and biomass (9,065.9 kgDM/ha/yr). (Table 3). As shown in the Erosion (RUSLE) section, Lower Benue (HA-4) has the highest per-hectare erosion rate (20.00 tons/ha/yr) despite being the smallest basin, suggesting heightened land-degradation vulnerability and a possible reduction in land productivity.

Table 3. Irrigation yield data in the four hydrological areas of the Niger-Benue River system. Potential estimates of crop, yield, biomass, and total production under irrigated conditions

Description	Hydrological Areas				Total
	HA-1	HA-2	HA-3	HA-4	
Formal Irrigation Dams (small to large)	52	56	46	28	182
Number of Beneficiaries (Farmers)	8280	1892	11355	2734	24261
Avg Farm Size Utilized (ha)	0.5	0.67	0.53	0.63	
Irrigated Crop Yield (ICY kg/ha/yr)	8856.3	8177.8	8060.7	7064.8	
Irrigated Biomass Yield (IBY KgDM/ha/yr)	11024.1	10565.9	10326.7	9065.9	
Production ('000 tons/yr)	1822.8	2118	1901.4	1117.7	

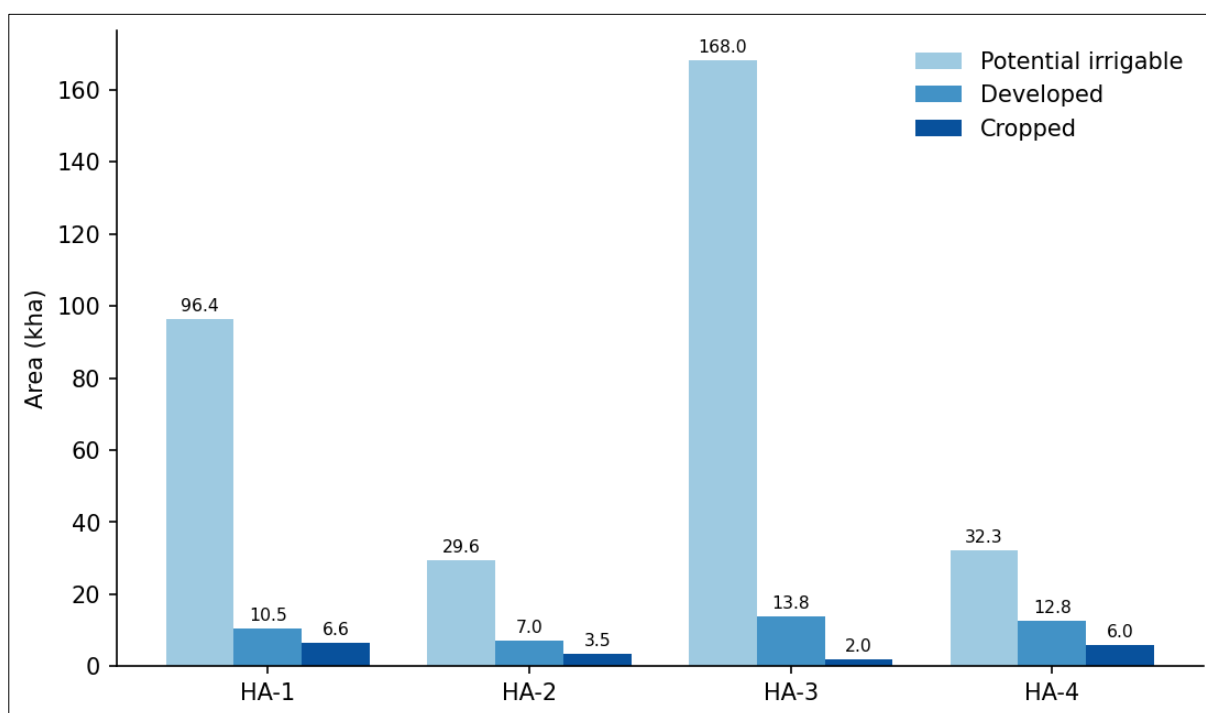


Figure 5. Agricultural potential of four hydrological areas in the Niger-Benue River system under irrigated conditions.

Source: Authors' data

3.5 Ecosystem Assessment of the Niger-Benue Hydrological Areas

Figure 6 presents ecosystem assessments for the four hydrological areas (HAs) within the Niger-Benue river system across four ecosystem dimensions: protected area (Figure 7), wetland (Figure 8), croplands (both rainfed and irrigated), and soil erosion potential (Figure 9). Results indicate that across HA-1–HA-4, the cumulative ET is 443.2 km³/yr. Of this, 33.6% comes from wetlands (71.7 km³/yr), protected areas (63.3 km³/yr), rainfed cropped land (13.9 km³/yr), and irrigated cropland (0.06 km³/yr). Annual ET is highest in Niger Basin (HA-1, 42.6) and Niger Central (HA-2, 50.6), and lowest in Lower Benue (HA-4, 21). Erosion risk follows a different pattern from area or ecosystem coverage. Lower Benue (HA-4) has the highest per-hectare erosion rate (20.15 tons/ha/yr) despite being the smallest basin, suggesting greater vulnerability to land degradation. Niger Central (HA-2) and Upper Benue (HA-3) also show high erosion rates (14.40 and 13.40 tons/ha/yr), while Niger North (HA-1) is markedly more stable at just 5.00 tons/ha/yr (Figure 6).

Ecosystem analysis of the Niger-Benue hydrological river system reveals that basins with higher protected/wetland coverage (Niger North) tend to show lower erosion, while Lower Benue — with the least protection and smallest wetland share — is the most erosion-vulnerable basin in the set. This suggests that conservation priorities across the four basins may need to be tailored differently: HA-1's wetlands warrant hydrological management focus,

while HA-2, HA-3, and especially HA-4 likely need stronger erosion control and soil conservation interventions relative to their protected-area investment.

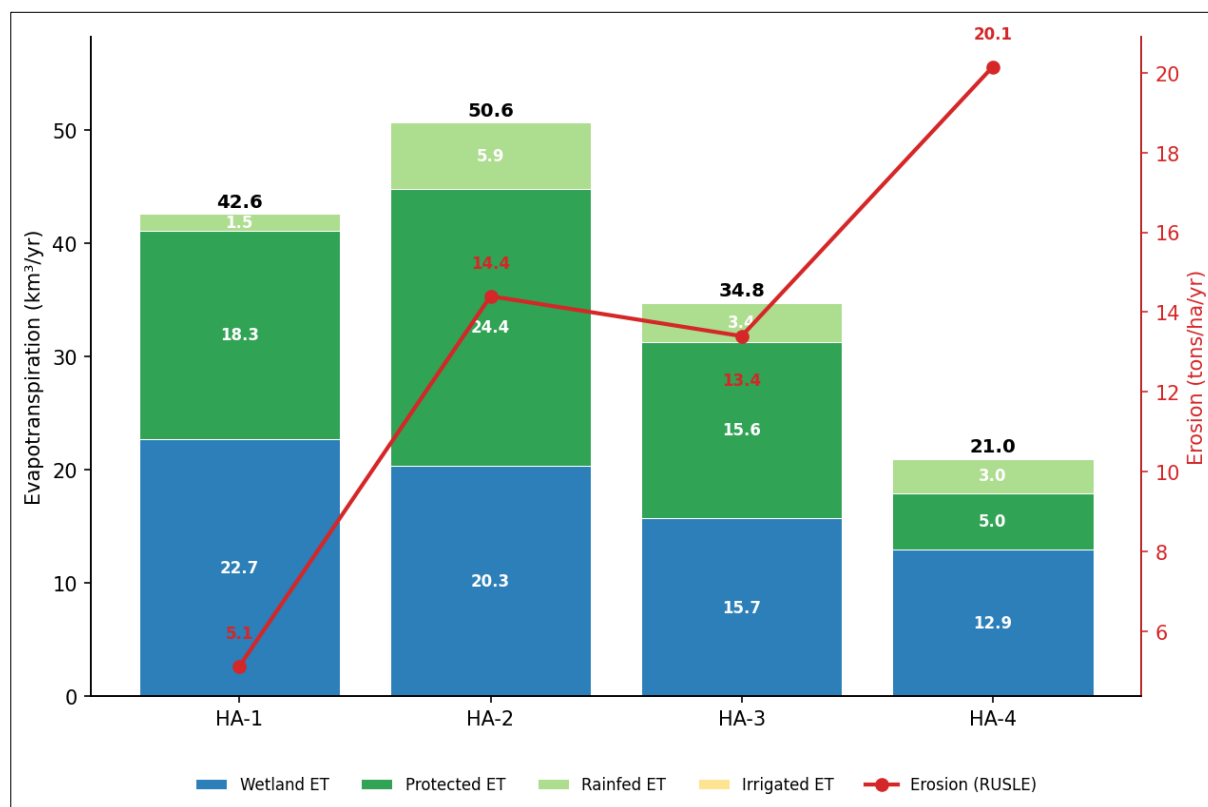


Figure 6. Ecosystem assessments in the four hydrological areas. *Source:* Authors' data

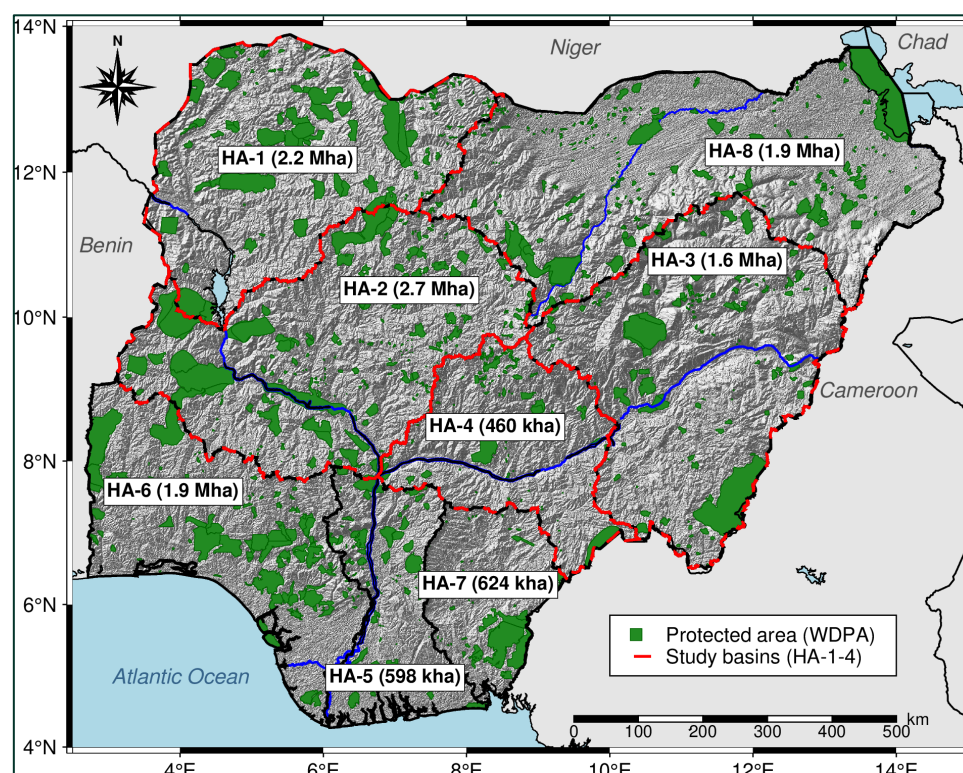


Figure 7. Protected areas within the Nigerian hydrological system. *Source:* Authors' data

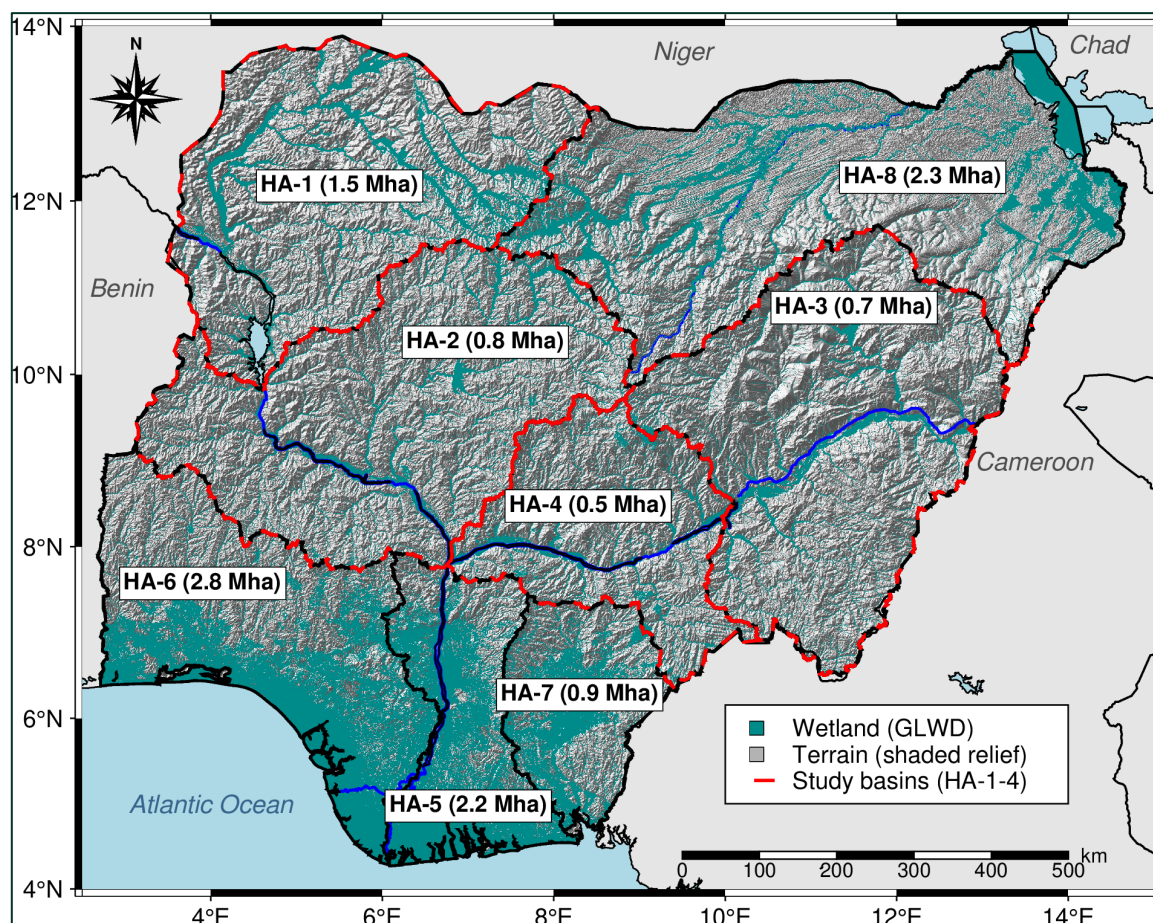


Figure 8. Wetlands within the Nigerian hydrological system. Source: Authors' data

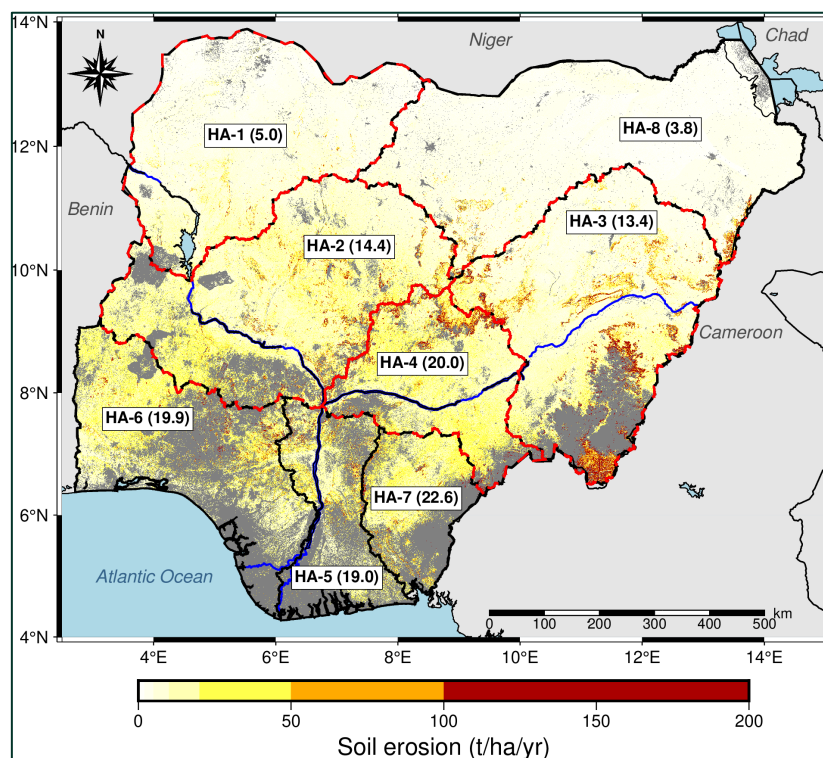


Figure 9. Soil erosion within the Nigerian hydrological system. Source: Authors

4. Discussion

Nigeria has extensive hydrological resources, particularly the Niger and Benue River systems, which offer substantial opportunities for irrigation expansion, hydropower generation, fisheries, and domestic water supply. However, inadequate infrastructure maintenance, low investment, and weak operational efficiency have often constrained the developmental benefits of these river systems (Ngene et al. 2021). As with most of SSA, research on the Water-Energy-Food-Ecosystem nexus in Nigeria has been somewhat fragmented. Few studies examine WEFE indicators and the spatial extent of hydrological response areas in the Niger-Benue river system. A study on WEFE indicators is required to optimize water–energy–food–environment connections, including water–energy (water for energy and energy for water) and water–food (water for food) and water–environment (water for environment) connections (Endo et al. 2017).

The Niger-Benue River system is a highly dynamic hydrological network with an estimated annual surface water potential of 200 BCM at the Lokoja confluence (Afolabi 2025) and contributes significantly to Nigeria's 52 BCM of total annual replenishable groundwater (Merem et al. 2017). An analysis of the system's four primary Hydrological Areas (HA-1 through HA-4) reveals distinct regional characteristics and resource distributions.

The Upper Benue (HA-3) is the most hydrologically active zone; it drives the system's runoff, generating the highest surface water volume (66.96 BCM) while also holding the second-highest groundwater storage (16.01 BCM). The Niger Basin (HA-1) holds the most groundwater (18.91 BCM), making it a critical buffer for sustaining crop water use during dry seasons. The Niger Central (HA-2) retains comparatively little groundwater (9.74 BCM) but generates a large surface runoff volume (58.76 BCM), providing vital stabilizing flow for the Niger side of the confluence. The Lower Benue (HA-4) has the smallest geographic footprint, shows intense runoff, and yields about twice the surface water per square kilometer as the Niger Basin. These hydrological differences are reflected in human interventions.

Cross-referencing irrigated cropland ET from the land cover analysis shows that irrigation is concentrated almost entirely in the Niger Basin and Upper Benue, the two basins with the most groundwater storage. Irrigated cropland ET is highest in the Upper Benue (0.031 km³/yr), closely followed by the Niger Basin (0.028 km³/yr), and more than an order of magnitude lower in Niger Central (0.0007 km³/yr) and Lower Benue (0.0009 km³/yr). Irrigation accounts for about 1.8% of total agricultural water use in the Niger Basin and 0.9% in the Upper Benue, compared with 0.01–0.03% in the other two. Niger Central illustrates the contrast: despite generating the second-highest surface runoff, it has almost no irrigated cropland and by far the highest rainfed cropland ET, suggesting that farmers there depend on direct rainfall and surface flow rather than groundwater-supported irrigation, consistent with the basin's low groundwater storage.

The pattern indicates that irrigation development is concentrated where a groundwater buffer exists, not simply where surface runoff is highest. Groundwater offers a reliable, on-demand supply through the dry season, whereas surface runoff is seasonal and often difficult to capture without storage or diversion infrastructure. This suggests that groundwater-supported irrigation is the most accessible entry point for expanding dry-season production in the Niger Basin and Upper Benue, while Niger Central, with abundant runoff but limited groundwater, may be better suited to surface-water management, such as storage, diversion, or water

harvesting, than to groundwater-based expansion. Two caveats apply. First, irrigated cropland remains a small share of total land and water use in all four basins, so the concentration described here is relative to a low overall baseline, and large potential remains untapped. Second, the irrigated versus rainfed split derives from the ESA CCI 300 m land cover classification, a satellite-based proxy for irrigation status rather than direct verification of scheme locations. With only four basins, the association between groundwater and irrigation is consistent with, but does not demonstrate, a causal link; existing schemes, market access, and infrastructure may also contribute. Field validation and scheme-level inventories would strengthen the interpretation.

An analysis of Nigeria's energy landscape across the four primary hydrological basins reveals a stark geographic divide between established hydropower infrastructure and untapped renewable potential. Currently, the nation's energy grid is heavily anchored by installations concentrated in just two regions. The Niger Central basin (HA-2) is the dominant powerhouse, generating 16,451 GWh/yr through major facilities, including the Jebba, Shiroro, and the recently operational Zungeru dams. The neighboring Niger Basin (HA-1) supplements this with 6,657.6 GWh/yr from the Kainji dam. Conversely, the Upper and Lower Benue regions currently have no recorded hydropower operations, highlighting a significant geographic disparity in traditional grid development. However, the regional narrative shifts dramatically when assessing next-generation renewable resources.

The Upper Benue basin (HA-3) emerges as a potential source for alternative energy development. It boasts the highest solar power potential, with over 49,000 hectares of suitable land, and also dominates biomass potential, with an estimated 72.1 million GJ of total energy. Even the smaller Lower Benue basin demonstrates significant solar and biomass capacity despite lacking hydro infrastructure. Strategically, Niger Central is the country's most versatile energy hub, ranking second in both solar and biomass potential while maintaining its hydropower dominance. Moving forward, to ensure energy security and equitable regional development, policymakers should prioritize diversifying investments toward the Upper Benue region. Capitalizing on its vast solar and biomass resources would decentralize Nigeria's energy generation and reduce over-reliance on the Niger Central hydropower corridor. The Niger Central basin is the most established for traditional hydropower, utilizing multiple large dams. The Upper Benue basin has the greatest untapped potential for other renewable energy sources, leading in both solar and biomass energy metrics. More detailed studies are recommended to better leverage the untapped energy potential of the Benue and Niger Basins.

Regarding agricultural productivity, the Lower Benue Basin is the smallest and least productive region across all agricultural metrics. The core trade-off remains between the Upper Niger Basin and Niger Central: the Niger North (HA-1) is the best region for maximizing per-hectare yield, but it requires an enormous amount of water to achieve this. Conversely, Niger Central represents the potential location for large-scale farming. In Nigeria, environmental degradation has become a major constraint to sustainable development, undermining the resilience of both rural and urban livelihoods. Across the Niger-Benue River system, this manifests as a set of interlocking ecological stresses: desertification in the northern drylands, gully erosion in the southeast, deforestation, and wetland degradation. Figure 6 lends empirical weight to this picture, revealing marked disparities across the four hydrological areas. Erosion rates under the RUSLE model range from a low of 5.00 tons/ha/yr in Niger North to a high of 20.00 tons/ha/yr in Lower Benue — a basin that,

despite being the smallest in area, carries the greatest erosion burden and the lowest protected-area coverage (6.10%).

This inverse relationship between basin size and degradation intensity suggests that erosion risk is driven less by scale than by land-use pressure and insufficient conservation investment. These pressures collectively reduce water quality, soil fertility, biodiversity, and livelihood opportunities, while increasing vulnerability to droughts, floods, and food insecurity. Nwambuko et al. (2025) noted that in ecologically vulnerable regions like North Central Nigeria, environmental sustainability is increasingly compromised by climate-induced flooding and deforestation, despite the presence of the Climate Change Act (2021) — a pattern consistent with Upper Benue's relatively high erosion rate (13.40 tons/ha/yr) alongside modest protected-area coverage (10.40%). Conversely, Niger North's comparatively low erosion rate coincides with its highest wetland share (11.36%) and substantial protected-area extent (16.51%), pointing to a measurable link between ecosystem protection and land stability.

Sustainability is currently framed through the Water-Energy-Food-Ecosystem (WEFE) Nexus, acknowledging that ecosystem health underpins national security. Figure 6's findings reinforce this framing: basins with higher protected/wetland coverage tend to show lower erosion, suggesting conservation priorities need to be tailored; HA-1's wetlands warrant hydrological management focus, while HA-2, HA-3, and especially HA-4 likely need stronger erosion control and soil conservation interventions.

5. Conclusions

Nigeria's extensive hydrological endowment—anchored by the Niger and Benue River systems—offers substantial untapped potential for irrigation expansion, hydropower generation, food systems enhancement, and environmental protection. The WEFE study in this paper confirms that the Niger-Benue River system underscores both the promise and fragility of Nigeria's WEFE nexus. With an estimated 200 BCM of surface water at the Lokoja confluence and 52 BCM of replenishable groundwater, the basin possesses resources capable of anchoring national water, energy, and food security. Yet this potential is unevenly distributed and often in tension: Upper Benue drives the system's hydrology and leads in untapped solar and biomass capacity, while Niger Central dominates existing hydropower and delivers the most efficient food output per unit of water. The Niger Basin, by contrast, offers the highest per-hectare yields but at a steep water cost, and Lower Benue—the smallest in area—bears the heaviest erosion burden and the weakest protected-area coverage. These disparities confirm that erosion, wetland loss, and energy access are governed less by basin size than by land-use pressure and conservation investment. Closing this gap demands coordinated, basin-specific policy rather than uniform intervention, positioning ecosystem resilience as the foundation on which water, energy, food security, and environmental sustainability must jointly rest.

6. References

- Abatzoglou, J.T.; Dobrowski, S.Z.; Parks, S.A.; Hegewisch, K.C. 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, 5, 170191. <https://doi.org/10.1038/sdata.2017.191>
- Adegbehin, A. B.; Yusuf, Y. O.; Iguisi, E. O.; Zubairu, I. 2016. Reservoir inflow pattern and its effects on hydroelectric power generation at the Kainji Dam, Niger State, Nigeria. *WIT Transactions on Ecology and the Environment*. <https://doi.org/10.2495/eid160211>
- Afolabi, M. 2025. Long-term streamflow discharge from the Niger River Basin into the delta region. *Hydrological Sciences Journal*, 70(7), 1038–1051. <https://doi.org/10.1080/02626667.2025.2478137>
- Akpoti, K.; Velpuri, N. M.; Mizukami, N.; Kagone, S.; Leh, M.; Mekonnen, K.; ... & Seid, A. 2024a. Advancing water security in Africa with new high-resolution discharge data. *Scientific Data*, 11(1), 1195. <https://doi.org/10.1038/s41597-024-04034-0>
- Akpoti, K.; Mekonnen, K.; Leh, M.; Owusu, A.; Dembélé, M.; Tinonetsana, P.; Seid, A.; Velpuri, N. M. 2024b. State of continental discharge estimation and modelling: Challenges and opportunities for Africa. *Hydrological Sciences Journal*, 69(15), 2124–2152. <https://doi.org/10.1080/02626667.2024.2402938>
- Amogu, O. 2022. Reservoir operation simulation for existing and planned hydropower projects on the Niger and Benue catchments in Nigeria. *E3S Web of Conferences*, 346, 03018. <https://doi.org/10.1051/e3sconf/202234603018>
- Arderne, C.; Zorn, C.; Nicolas, C.; Koks, E. E. 2020. Predictive mapping of the global power system using open data. *Scientific Data*, 7(1). <https://doi.org/10.1038/s41597-019-0347-4>
- Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; Yumkella, K.K. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, 39(12), 7896–7906. <https://doi.org/10.1016/j.enpol.2011.09.039>
- Biggs, E.M.; Bruce, E.; Boruff, B.; Duncan, J.M.A.; Horsley, J.; Pauli, N.; McNeill, K.; Neef, A. 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy*, 54, 389–397. <https://doi.org/10.1016/j.envsci.2015.08.002>
- Borrelli, P.; Ballabio, C.; Yang, J.E.; Robinson, D.A.; Panagos, P. 2022. GloSEM: High-resolution global estimates of present and future soil displacement in croplands by water erosion. *Scientific Data*, 9(1), 406. <https://doi.org/10.1038/s41597-022-01489-x>
- Climate Change Act, 2021*. Abuja, Nigeria: Federal Republic of Nigeria. Available at: <https://ossapcfse.org/wp-content/uploads/2025/03/Climate-Change-Act-2021-Gazette-Version.pdf> (accessed on July 24, 2026).
- Conway, D.; Dalin, C.; Landman, W.A.; Osborn, T.J. 2017. Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. *Nature Energy*, 2, 946–953. <https://doi.org/10.1038/s41560-017-0037-4>

Daher, B.T.; Mohtar, R.H. 2015. Water–energy–food (WEF) nexus tool 2.0: Guiding integrative resource planning and decision-making. *Water International*, 40(5–6), 748–771. <https://doi.org/10.1080/02508060.2015.1074148>

Endo, A.; Tsurita, I.; Burnett, K.; Orenco, P.M. 2017. A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology: Regional Studies*, 11, 20–30. <https://doi.org/10.1016/j.ejrh.2015.11.010>

ESMAP (Energy Sector Management Assistance Program). 2019. Global Solar Atlas 2.0 Technical Report. Washington, DC: World Bank. Available at: <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/529431592893043403>

FAO (Food and Agriculture Organization); IIASA (International Institute for Applied Systems Analysis). 2025. *Global Agro-Ecological Zones version 5 (GAEZ v5) Model Documentation*. Rome, Italy: FAO; Laxenburg, Austria: IIASA. Available at: <https://github.com/un-fao/gaezv5/wiki> (accessed on April 17, 2026).

Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D. & Moore, R. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18–27. <https://doi.org/10.1016/j.rse.2017.06.031>

Johnson, M. 2026. Nigeria: Country water resources. *Climate Scorecard*. Available at: <https://www.climatecard.org/2026/06/nigeria-country-water-resources/> (accessed on July 21, 2026).

Kerner, H.; et al. 2024. How accurate are existing land cover maps for agriculture in Sub-Saharan Africa? *Scientific Data*, 11(1), 486. <https://doi.org/10.1038/s41597-024-03306-z>

Kinnell, P.I.A. 2010. Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. *Journal of Hydrology*, 385(1–4), 384–397.

Lehner, B.; Beames, P.; Mulligan, M.; Zarfl, C.; De Felice, L.; van Soesbergen, A.; Thieme, M.; Garcia de Leaniz, C.; Anand, M.; Belletti, B.; Brauman, K.A.; Januchowski-Hartley, S.R.; Lyon, K.; Mandle, L.; Mazany-Wright, N.; Messenger, M.L.; Pavelsky, T.; Pekel, J.-F.; Wang, J.; Wen, Q.; Wishart, M.; Xing, T.; Yang, X.; Higgins, J. 2024. The Global Dam Watch database of river barrier and reservoir information for large-scale applications. *Scientific Data*, 11, 1069. <https://doi.org/10.1038/s41597-024-03752-9>

Lehner, B.; Anand, M.; Fluet-Chouinard, E.; Tan, F.; Aires, F.; Allen, G.H.; Bousquet, P.; Canadell, J.G.; Davidson, N.; Ding, M.; Finlayson, C.M.; Gumbrecht, T.; Hilarides, L.; Hugelius, G.; Jackson, R.B.; Korver, M.C.; Liu, L.; McIntyre, P.B.; Nagy, S.; Olefeldt, D.; Pavelsky, T.M.; Pekel, J.-F.; Poulter, B.; Prigent, C.; Wang, J.; Worthington, T.A.; Yamazaki, D.; Zhang, X.; Thieme, M. 2025. Mapping the world's inland surface waters: An upgrade to the Global Lakes and Wetlands Database (GLWD v2). *Earth System Science Data*, 17, 2277–2329. <https://doi.org/10.5194/essd-17-2277-2025>

MacDonald, A. M.; Bonsor, H. C.; Ó Dochartaigh, B. É.; Taylor, R. G. 2012. Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, 7, 024009. <https://doi.org/10.1088/1748-9326/7/2/024009>

- Merem, E. C.; Twumasi, Y.; Wesley, J.; et al. 2017. Analyzing water management issues using GIS: The case of Nigeria. *Geosciences*, 7, 20–46.
<https://doi.org/10.5923/j.geo.20170701.03>
- Ngene, B.U.; Nwafor, C.O.; Bamigboye, G.O.; Ogbiye, A.S.; Ogundare, J.O.; Akpan, V.E. 2021. Assessment of water resources development and exploitation in Nigeria: A review of integrated water resources management approach. *Heliyon*, 7(1), e05955.
<https://doi.org/10.1016/j.heliyon.2021.e05955>
- Nwambuko, T.C.; Egbuchulam, M.U.; Amanze, H.U. 2025. Climate change and environmental governance in Nigeria: A focus on North Central region. *Asian Research Journal of Arts & Social Sciences*, 23(10), 200–219.
<https://doi.org/10.9734/arjass/2025/v23i10813>
- Ringler, C.; Bhaduri, A.; Lawford, R. 2013. The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability*, 5(6), 617–624. <https://doi.org/10.1016/j.cosust.2013.11.002>
- Sanogo, K.; Birhanu, B.Z.; Sanogo, S.; Ba, A. 2023. Landscape pattern analysis using GIS and remote sensing to diagnose soil erosion and nutrient availability in two agroecological zones of Southern Mali. *Agriculture & Food Security*, 12, 4.
<https://doi.org/10.1186/s40066-023-00408-6>
- Santoro, M.; Cartus, O. 2026. *ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the years 2005–2012 and 2015–2024, v7.0*. NERC EDS Centre for Environmental Data Analysis.
<https://dx.doi.org/10.5285/6429d1aafe1e43b9b414e4a5a7f8b903>
- Senay, G.B.; Parrish, G.E.L.; Schauer, M.; Friedrichs, M.; Khand, K.; Boiko, O.; Kagone, S.; Dittmeier, R.; Arab, S.; Ji, L. 2023. Improving the operational simplified surface energy balance evapotranspiration model using the forcing and normalizing operation. *Remote Sensing*, 15(1), 260. <https://doi.org/10.3390/rs15010260>
- Simpson, G.B.; Jewitt, G.P.W. 2019. The water-energy-food nexus in the anthropocene: Moving from ‘nexus thinking’ to ‘nexus action’. *Current Opinion in Environmental Sustainability*, 40, 117–123. <https://doi.org/10.1016/j.cosust.2019.10.007>
- UNEP-WCMC (United Nations Environment Programme World Conservation Monitoring Centre); IUCN (International Union for Conservation of Nature). 2024. *Protected Planet: The World Database on Protected Areas (WDPA)*. Cambridge, UK: UNEP-WCMC; IUCN. Available at: <https://www.protectedplanet.net> (accessed on April 17, 2026).
- Vigiak, O.; Borselli, L.; Newham, L.T.H.; McInnes, J.; Roberts, A.M. 2012. Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio. *Geomorphology*, 138(1), 74–88. <https://doi.org/10.1016/j.geomorph.2011.08.026>
- Zanaga, D.; Van De Kerchove, R.; De Keersmaecker, W.; Souverijns, N.; Brockmann, C.; Quast, R.; Wevers, J.; Grosu, A.; Paccini, A.; Vergnaud, S.; Cartus, O.; Santoro, M.; Fritz, S.; Georgieva, I.; Lesiv, M.; Carter, S.; Herold, M.; Li, L.; Tsendbazar, N.-E.; Arino, O. 2021. *ESA WorldCover 10 m 2020 v100* (Version v100) [Data set]. Zenodo.
<https://doi.org/10.5281/zenodo.5571936>



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