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Space-Based Driven Approach to Hydrological Analysis of Prospective Watersheds and Dams for Sustainable Irrigation in Niger State, Nigeria

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ABSTRACT

This study investigates the hydrological characteristics of prospective watersheds in Niger State, Nigeria, using a space-based approach to support enhanced and sustainable irrigation agriculture. The methodology integrates climatic and hydrological data to develop a comprehensive, data-rich framework for water resource management within geo-hydrological units, supporting agricultural planning and environmental protection. The study employs statistical computation of land resources using Sentinel-2 imagery in Google Earth Engine, along with spatial analysis of hydrological systems using Digital Elevation Model (DEM) data for stream network analysis. A Multi-Criteria Decision Analysis (MCDA) was applied to identify potential reservoir sites, incorporating topography, stream order, catchment area, and slope as key criteria. Criteria weights were assigned using expert judgment and a pairwise comparison approach, with topography and stream order receiving the highest weights given their primary influence on water accumulation and flow routing.

The study delineated twenty-two (22) prospective watersheds as geo-hydrological units, ranging in size from 675.77 km² to 12,358.8 km². The circularity ratios indicate that more than 55% of the watersheds have values between 0.4 and 0.5, suggesting irregular shape, moderate surface runoff, and high permeability, characteristics consistent with structural controls from remnant tectonic features in the underlying crystalline rocks. Multiple factors, including topography, land use, soil type, geology, and climate, influence the hydrological characteristics of these watersheds. Stream networks display a dendritic pattern flowing predominantly NE–SW, parallel to the Nigerian regional lineament, indicating structural control and confirming their role as conduits for groundwater recharge. The failed triple-arm rifting system responsible for the Niger and Benue river valleys and sedimentary basins has exerted significant structural influence on the region.

Niger State has an agricultural land area of approximately 25,361.27 km², which accounts for more than 80% of the state's total land area, while water bodies cover 460.51 km², indicating substantial irrigation potential. The prospective water reservoirs identified in this study have the combined capacity to irrigate more than 22,000 km² of agricultural land. Specifically, the Shiroro and Zungeru Dams can irrigate 2,642.41 km² of agricultural land within their basins, while the Kainji and Jebba Dams have the capacity to irrigate approximately 7,000 km² and 4,000 km², respectively. The study recommends effective multi-sectoral collaboration, participatory planning, integrated management, and adaptive strategies to sustainably manage these prospective watersheds, with the overarching goal of balancing ecological, economic, and social needs through integrated land and water resource management in support of SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation).

Keywords: hydrological analysis, watershed delineation, dam siting, irrigation agriculture, geospatial technology, multi-criteria decision analysis, Niger State, sustainability.

INTRODUCTION

Watersheds and dams are integral to the effectiveness and sustainability of irrigation systems. Their role in providing reliable water supply, preserving soil health, and supporting effective water management is critical for agricultural productivity. Nigeria possesses substantial prospective watersheds and dams that remain largely underutilized (Shanono et al., 2024). Identifying these potential watersheds is a necessary precondition before implementing planning interventions for agricultural development (Pushkar et al., 2016). These watersheds and dams also benefit ecosystems by ensuring consistent water management, enhancing food security, and promoting sustainable irrigation agriculture. However, the scarcity of comprehensive watershed and dam data has significant global implications for irrigation agriculture and food security, particularly in developing countries. Fundamental land and water resource management principles, including watershed development and catchment-level planning, should be prioritized to ensure Nigeria's environmental and agricultural sustainability. Geospatial approaches that integrate remote sensing and Geographic Information Systems (GIS) are essential for evaluating, characterizing, and managing watersheds to achieve sustainable irrigated agriculture. This methodology combines climatic, hydrological, and socioeconomic data into a comprehensive, geographically accurate, and data-rich framework for water management, agricultural planning, and environmental protection. From a geospatial perspective, analysing a watershed's hydrological properties is vital for effective water collection and management for food production. Niger State has abundant land and water resources and hosts a large number of potential watersheds, also known as geo-hydrological units, that are suitable for irrigation agriculture (Adeniyi et al., 2023). These watersheds vary considerably in size, shape, and structure, ranging from small, localized catchments to vast river basins covering entire regions. Their hydrological characteristics are influenced by land use, soil type, geology, topography, and climate. Niger State has distinct hydrological characteristics that differentiate it from other states in Nigeria. The state is defined by two major river systems: the Niger River, which forms its southern boundary, and the Kaduna River, which traverses the eastern portion. The Niger River, Africa's third-longest river, flows through the state for approximately 630 kilometres, creating a natural boundary with Kebbi State and forming the expansive Kainji Lake, covering over 1,300 square kilometres. The Kaduna River, a major tributary of the Niger, travels approximately 210 kilometres through the state's eastern districts before joining the Niger River near Pategi (Niger State Ministry of Water Resources, 2023). These river systems and their tributaries form extensive floodplains, wetlands, and stream networks that drain into the River Niger, which flows through the Niger–Benue confluence at Lokoja before reaching the Niger Delta. Recognizing the enormous, untapped potential of these water resources, this study aims to identify and characterize prospective watersheds in Niger State using geospatial technologies as a prerequisite for evidence-based planning interventions for agricultural development, in alignment with SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation) (Panjala et al., 2023).

Study Area

Niger State, located in Nigeria's north-central region, is one of the largest states by land area. The state covers approximately 76,363 square kilometres and lies between latitudes 8°20'N and 11°30'N, and longitudes 3°30'E and 7°20'E. It accounts for approximately 8.3% of Nigeria's total land area (National Bureau of Statistics [NBS], 2023). As shown in Figure 1, the state shares borders with Zamfara and Kebbi States to the north, Kaduna State and the Federal Capital Territory to the east, Kogi and Kwara States to the south, and the Republic of Benin to the west, positioning it as a strategic gateway between northern and southern Nigeria (Niger State Government [NSG], 2023).

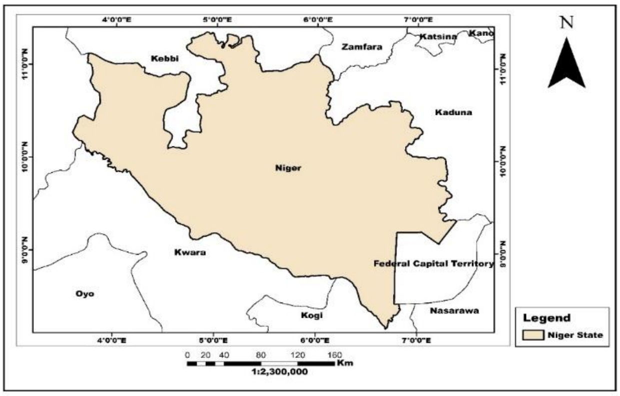

Figure 1: The Study Area (Niger State)

Rainfall Distribution and Patterns

Niger State experiences significant spatial variation in precipitation. As revealed in Figure 2, the southeastern region receives the highest rainfall, reaching up to 39.4 cm, while the northern and northwestern portions record lower precipitation levels of approximately 25.2 cm. This north–south rainfall gradient reflects the state's position in Nigeria's Middle Belt region, where the humid southern climate transitions into the drier Sahelian conditions of the north. Annual rainfall ranges from 1,100 mm in the northern areas to 1,600 mm in the southern regions (Nigerian Meteorological Agency [NIMET], 2023), with precipitation concentrated between April and October. Peak rainfall typically occurs in August and September, when monthly totals can exceed 250 mm in the wettest areas. The state's southern districts benefit from their proximity to moisture-laden air masses from the Atlantic Ocean, which results in longer rainy seasons and higher annual precipitation totals.

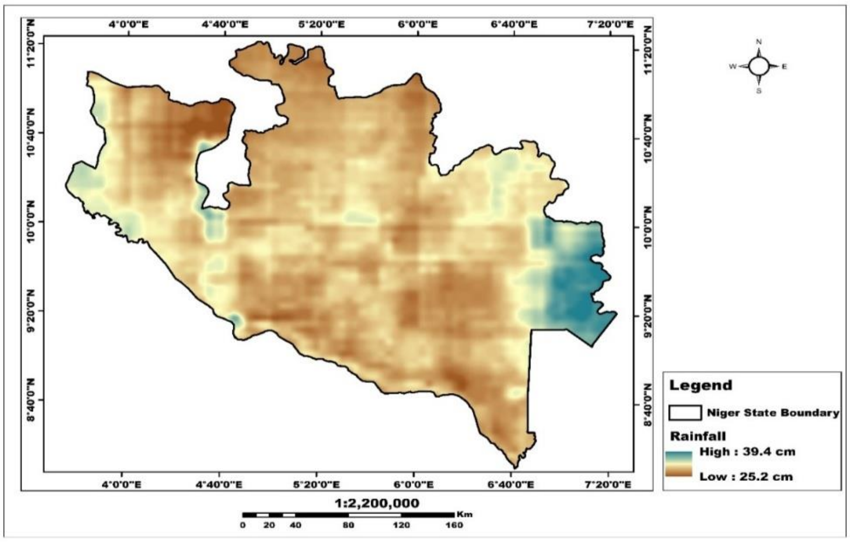

Figure 2: Distribution of Annual Rainfall in Niger State

Relative Humidity

The relative humidity across Niger State ranges from 37.0% in the driest areas to 94.7% in the most humid zones (Figure 3). The highest humidity levels are concentrated along river valleys and in the southeastern region, where they create distinct microclimates favourable for specific vegetation types and agricultural practices. Humidity fluctuations follow the seasonal precipitation cycle, with peak levels occurring during the rainy season (June to September), when atmospheric moisture content remains consistently high. During this period, morning humidity commonly exceeds 80% across most of the state. Conversely, the Harmattan season brings extremely dry conditions, with humidity levels frequently dropping below 40% (NIMET, 2023), leading to increased evapotranspiration, water stress for crops, and respiratory discomfort among residents.

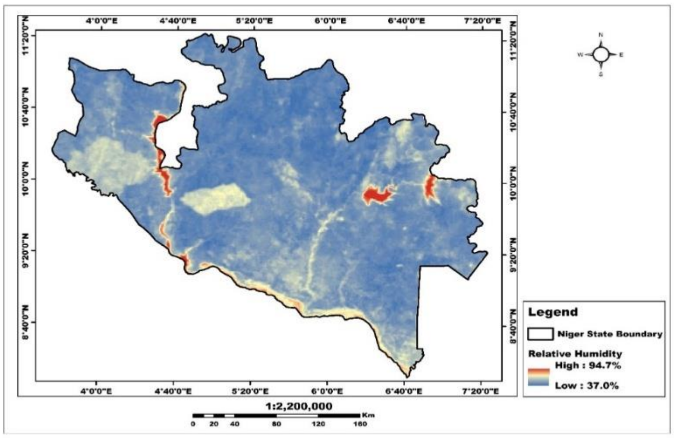

Figure 3: Relative Humidity of Niger State

Temperature Variation

Figure 4 presents the temperature distribution across Niger State, which ranges from 24.0°C in cooler highland pockets to 37.2°C in the hottest zones. The temperature pattern exhibits an inverse relationship with elevation: elevated areas, particularly in the central region, display slightly cooler temperatures than surrounding lowlands. Average temperatures fluctuate between 22°C and 36°C throughout the year (NIMET, 2023), with marked seasonal variations. The hottest period spans from March to May, immediately preceding the onset of the rainy season, when maximum temperatures regularly exceed 35°C and occasionally approach 40°C in the northern districts. The relatively cooler period occurs during the Harmattan season (November to February), when nighttime temperatures can fall to 15°C, producing a significant diurnal temperature range that affects both agricultural activities and human wellbeing.

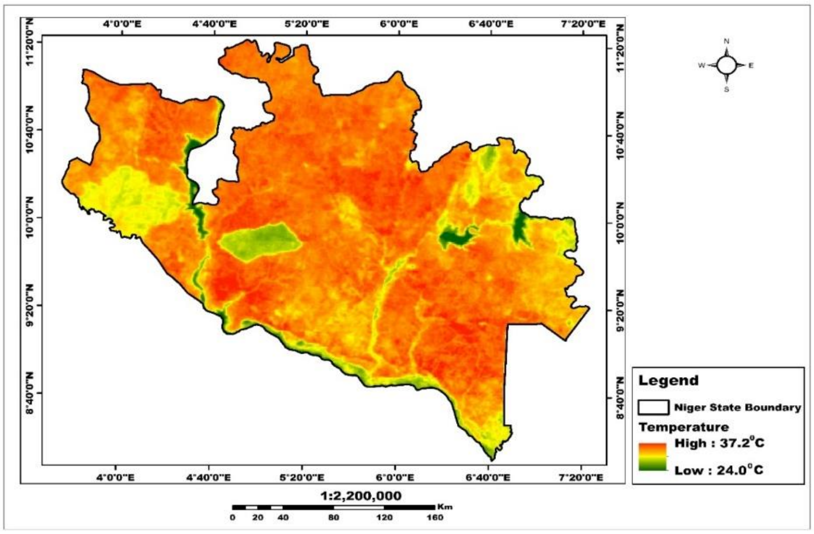

Figure 4: Distribution of Annual Temperature in Niger State

Geological Setting

Niger State is underlain predominantly by the Nigerian Basement Complex, consisting of Precambrian igneous and metamorphic rocks covering approximately 65% of the state's area (Nigerian Geological Survey Agency [NGSA], 2021). This basement is characterized by granites, gneisses, migmatites, and schists dating to the Pan-African orogeny. Some areas are overlain by sedimentary formations: the Bida Basin, a northwest-trending depression filled with Cretaceous to Tertiary sediments including sandstones, siltstones, claystones, and ironstones, underlies parts of the northeast, while the Sokoto Basin, present in smaller portions of the northwest, features limestone and shale formations (Federal Ministry of Mines and Steel Development, 2022).

The state's topography features expansive plains, occasional hills, and inselbergs, with elevations ranging from 150 meters in the Kaduna River valley to over 650 meters in the highlands near Kagara (NGSA, 2021). This varied topography influences local drainage patterns, agricultural potential, and settlement distribution. Significant mineral deposits include tantalite, gold, talc, iron ore, and feldspar, contributing to the state's economic base (Ministry of Solid Minerals Development, 2022).

The soils of Niger State reflect the diversity of parent materials, topography, and climate, with the most productive agricultural soils found in the floodplains of major rivers and their tributaries (Niger State Ministry of Agriculture, 2023).

Structurally, the area has been significantly influenced by the tectonic tensions associated with the failed triple-arm rifting system, which led to the formation of the Niger and Benue river valleys and their associated sedimentary basins. These structural controls are expressed in the elongated shape of many watersheds and the NE–SW orientation of stream networks, which correspond to major lineaments in the Nigerian Basement Complex (NGSA, 2021).

Topography

Niger State presents a diverse topography that transitions dramatically across its extent, from undulating northern plains and plateaus to more rugged southern terrain (Figure 5). The southwestern border features the Niger River carving a fertile valley with lush floodplains contrasting against drier savannah regions, while the central portions showcase rolling hills with isolated inselbergs and dramatic rock formations, particularly around Zuma Rock. This elevation gradient generates diverse ecosystems ranging from lowland forests and wetlands near major rivers, to savannah woodlands at middle elevations, and sparser vegetation in the higher northeastern regions. These topographic variations ultimately influence the state's ecological zones and agricultural practices.

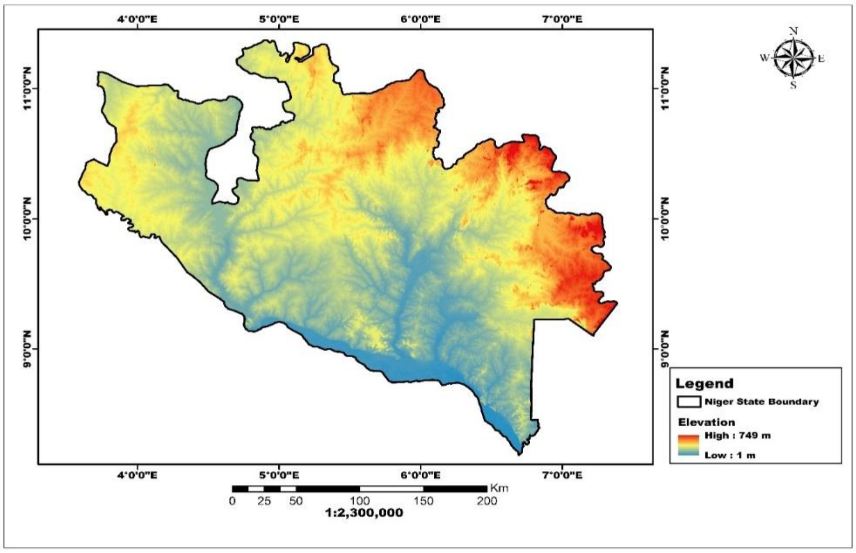

Figure 5: Elevation Map of Niger State

Hydrological Characteristics

Niger State's hydrology is defined by two major river systems: the Niger River, which forms its southern boundary, and the Kaduna River, which traverses the eastern portion of the state. These rivers and their tributaries create extensive floodplains that support agricultural activities and provide opportunities for fishing and transportation (Niger State Ministry of Water Resources, 2023). Other significant water bodies include the Gbako, Gurara, and Chanchaga Rivers, which collectively form a dense drainage network across the state (Niger State Hydrological Services Agency, 2022). The Kainji and Shiroro hydroelectric dams, situated on the Niger and Kaduna Rivers respectively, represent major water infrastructure with significant irrigation and power generation potential (Niger State Ministry of Environment, 2022).

METHODOLOGY

Data Acquisition

This research commenced with comprehensive data acquisition for Niger State, Nigeria. High-resolution satellite imagery, Digital Elevation Models (DEMs), and existing geospatial datasets, including annual temperature, rainfall, and humidity data, were obtained from multiple sources, primarily USGS Earth Explorer, Copernicus Open Access Hub, and Google Earth Engine. These datasets were subsequently processed using ArcGIS 10.8 software. Different satellite image scenes were mosaicked into a single composite image to cover the full spatial extent of the study area. Band combination was then applied to produce a false colour composite for land cover classification. All spatial datasets were standardized to the UTM projection (Zone 32N) and resampled to a uniform 30-meter spatial resolution to facilitate seamless integration. A structured geodatabase was established to maintain data integrity throughout the analytical process, with appropriate metadata documentation for each layer. This initial preparation stage was critical for ensuring spatial and temporal consistency across the diverse datasets from varied sources and collection periods. The overall analytical workflow is illustrated in Figure 6.

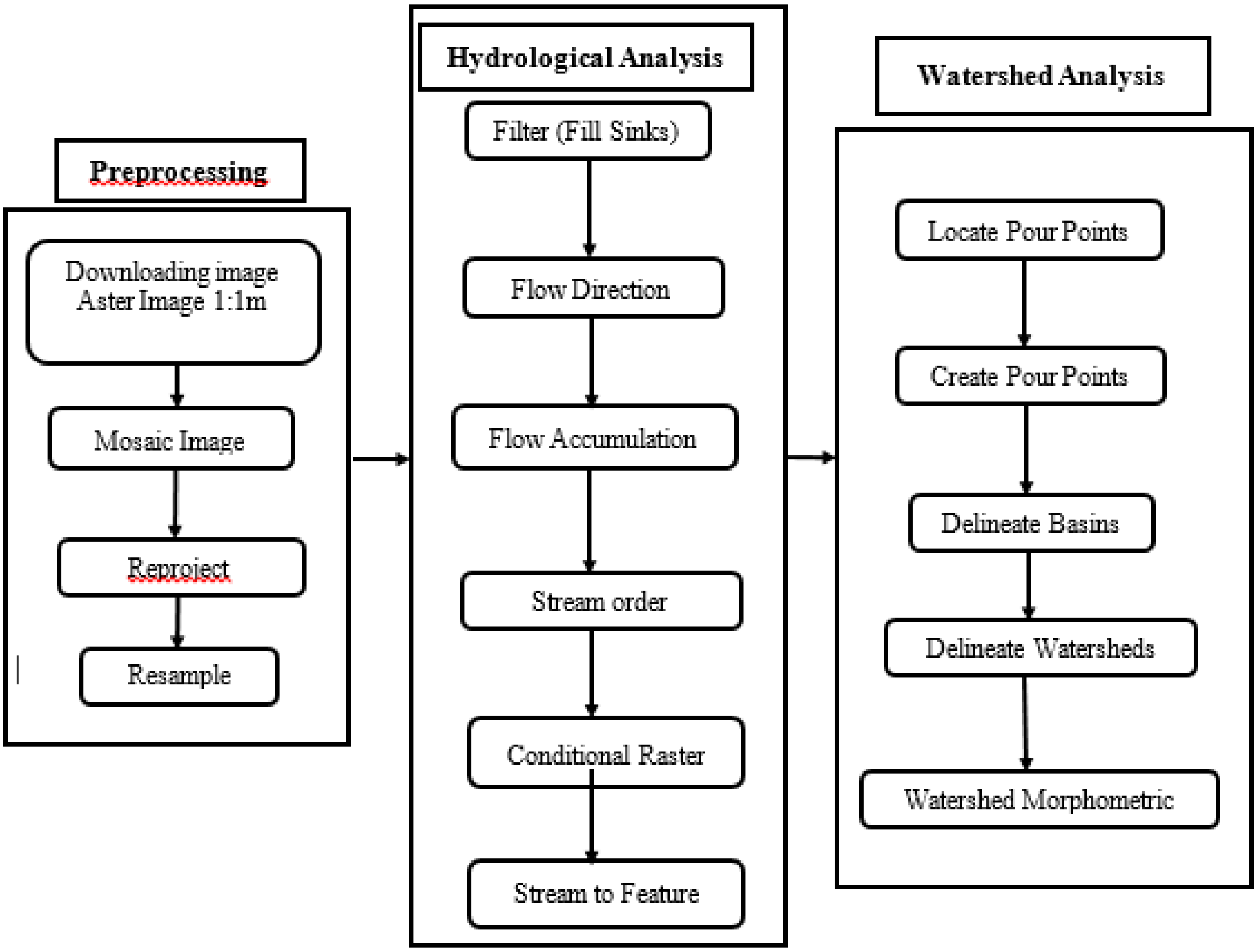

Figure 6: Flow Chart of Research Methodology

Climatic Data Analysis

The climate variable mapping phase focused on visualizing three critical parameters: relative humidity, rainfall distribution, and temperature patterns. Relative humidity was derived from satellite-based atmospheric moisture data, which was processed and spatially interpolated using the Inverse Distance Weighting (IDW) method to generate a continuous surface across the study area.

The resulting map revealed significant spatial variation, with humidity values ranging from 37.0% in central regions to 94.7% along specific western boundaries and waterways, reflecting microclimatic differences driven by topography, vegetation cover, and proximity to water bodies. The rainfall distribution map was generated by processing precipitation data from multiple meteorological stations on Google Earth Engine, interpolated and validated against historical records from NIMET.

This analysis revealed notable precipitation gradients across the state, with distinct wet and dry zones corresponding to topographic features and regional climatic patterns. Temperature distribution was mapped using thermal infrared bands from satellite imagery, revealing thermal hotspots and cooler zones that correlate with both natural landscape features and anthropogenic influences.

Land Use and Land Cover Analysis

Land cover classification was performed using a supervised maximum likelihood classification technique applied to multi-spectral satellite imagery. Training samples were carefully selected for each land cover category based on field data and high-resolution reference imagery. The classification identified eight distinct Land Use/Land Cover (LULC) classes: forest, shrubland, grassland, agricultural land, built-up areas, water bodies, wetlands, and rock outcrops. This detailed categorization enabled comprehensive landscape characterization essential for understanding hydrological processes and watershed dynamics. Post-classification refinement included majority filtering and contextual correction to minimize salt-and-pepper noise effects. Accuracy assessment was conducted using a confusion matrix against independent validation points, yielding an overall classification accuracy of 87% and a Kappa coefficient of 0.83. The final LULC map clearly illustrated the dominance of agricultural land across Niger State.

Hydrological Analysis and Watershed Delineation

Watershed delineation followed a systematic approach grounded in hydrological modelling principles. A hydrologically corrected DEM was first prepared by filling sinks and removing surface imperfections to create a continuous flow surface accurately representing the terrain. Flow direction and flow accumulation analyses were then performed to identify natural drainage patterns and stream networks. Watershed boundaries were delineated based on topographic divides identified from the corrected DEM, with pour points defined at locations of concentrated flow accumulation corresponding to dam sites or natural outlets.

Drainage density calculations provided quantitative metrics for comparative analysis, revealing areas of high surface runoff potential, which were visualized through a multi-tiered intensity classification. Watersheds were further characterized based on morphometric parameters including slope, permeability, stream density, and circularity ratio. Potential reservoir sites were identified through a Multi-Criteria Decision Analysis (MCDA) that incorporated topographic suitability, stream order, catchment area, and proximity to settlements as evaluation criteria.

Criteria weights were assigned using a pairwise comparison matrix based on expert judgment, with topography and stream order receiving the highest relative weights of 0.35 and 0.30, respectively, given their primary influence on water accumulation and flow dynamics. Each candidate site was evaluated using the resulting weighted scoring system, and sites with the most favourable combinations of these factors were selected as prospective reservoir locations.It is important to acknowledge the limitations associated with the remote sensing data and modelling approach used in this study.

The 30-meter resolution DEM may not capture fine-scale topographic features, which could introduce minor errors in watershed boundary delineation, particularly in low-relief areas. Additionally, the LULC classification was not validated with ground-truth surveys in all sub-regions, and the MCDA weights, while grounded in hydrological principles, carry an element of subjectivity. Future research should incorporate field validation, ground-truthing of classified maps, and integration of socioeconomic data to enhance the comprehensiveness and accuracy of the watershed management framework.

RESULTS AND DISCUSSION

Watersheds and Natural Resources in the Study Area

The study identified twenty-two (22) geo-hydrological units (watersheds) distributed across the study area, ranging in size from 675.77 km² to 12,358.8 km² (Tables 2 and 3). Identifying appropriate watersheds is a prerequisite for implementing evidence-based planning interventions for sustainable agricultural development. Figure 7 presents the spatial extent of existing dams and the distribution of stream networks across the identified watersheds.

As shown in Table 1, agricultural land covers 25,361.27 km², accounting for more than 80% of the total land area of Niger State. Water bodies cover 460.51 km², confirming the availability of water resources for irrigation agriculture. The existing dams are located at Kainji, Jebba, and Shiroro, with the Zungeru Dam positioned to the west of Shiroro. A wetland area of 100.29 km² presents additional potential for rice cultivation. Rock outcrops play a significant role in shaping several hydrological variables in the study area. This pattern is not unique to Niger State but is characteristic of Nigeria's north-central region, where crystalline Basement Complex outcrop and their underlying structural features have consistently influenced the formation and behaviour of hydrological systems.

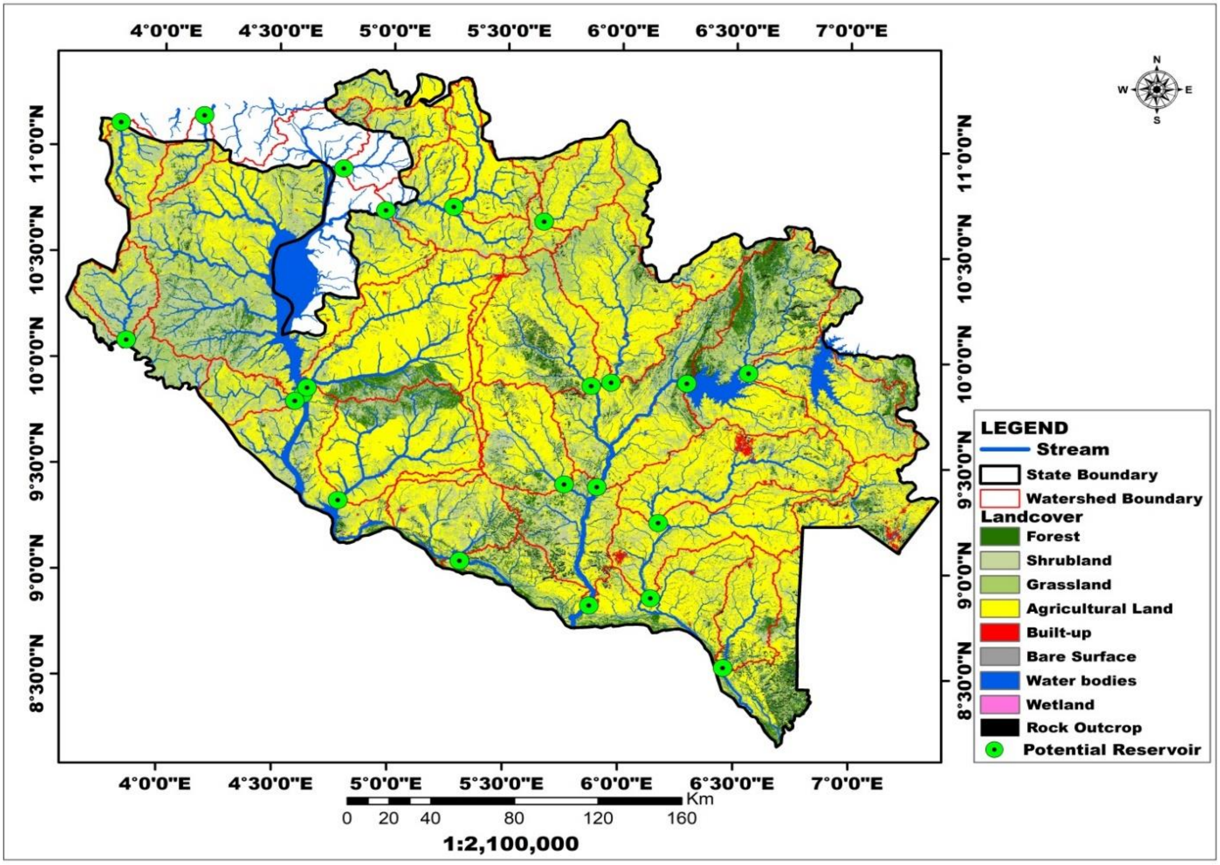

Figure 7: Spatial Distribution of Natural Resources in Niger State

Table 1: Natural Resources of Niger State

S/N	Land Cover Class	Area (km²)
1	Forest	5,176.08
2	Shrubland	9,505.86
3	Grassland	8,056.98
4	Agricultural Land	25,361.27
5	Built-up	482.68
6	Bare Surface	137.74
7	Water Bodies	460.51
8	Wetland	100.29

Watersheds and Potential Water Reservoirs

In geo-hydrological units, water flows downslope through a network of streams to common outlets, distributing flow to rivers and reservoirs. Figures 8 and 9 present the spatial distribution of pour points (potential dam sites) and the twenty-two (22) delineated watersheds identified as prospective water reservoirs within the study area. The stream networks exhibit a dendritic pattern flowing predominantly from NE to SW, an orientation consistent with Nigerian regional lineaments, confirming that flow patterns are structurally controlled by the underlying geology. Understanding these morphometric and structural parameters provides valuable insights into water flow behaviour, watershed storage capacity, and groundwater recharge dynamics. Land use, soil type, geology, topography, and climate collectively characterize each watershed in Niger State and influence its hydrological response.

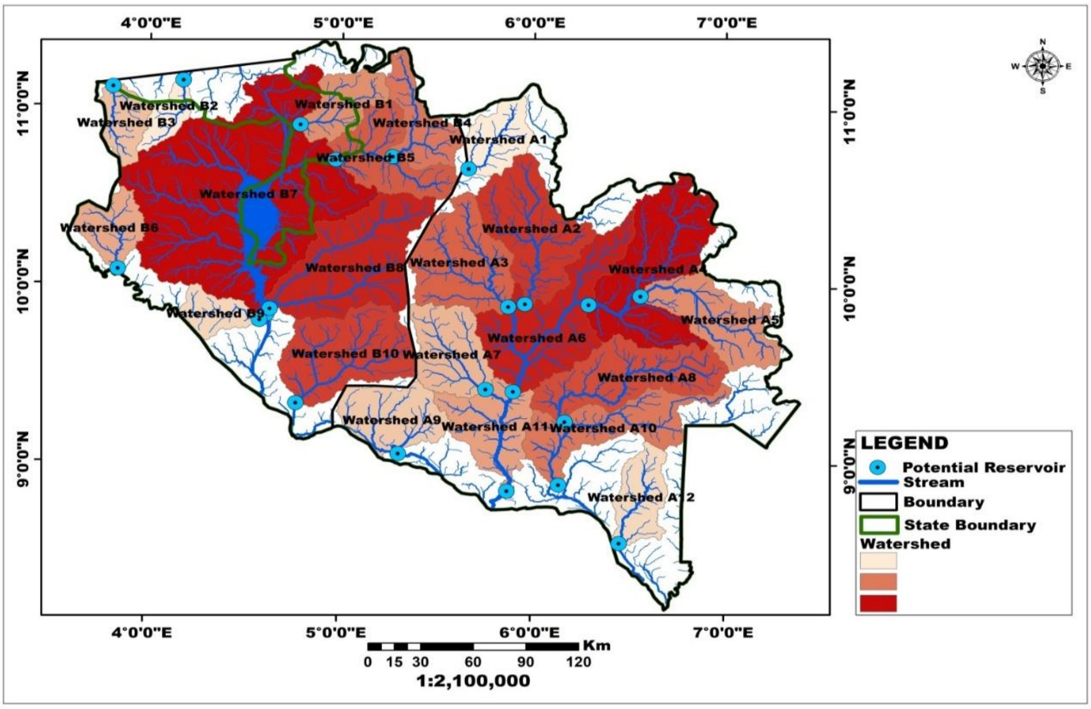

Figure 8: Delineated Watersheds for Irrigation Agriculture in Niger State

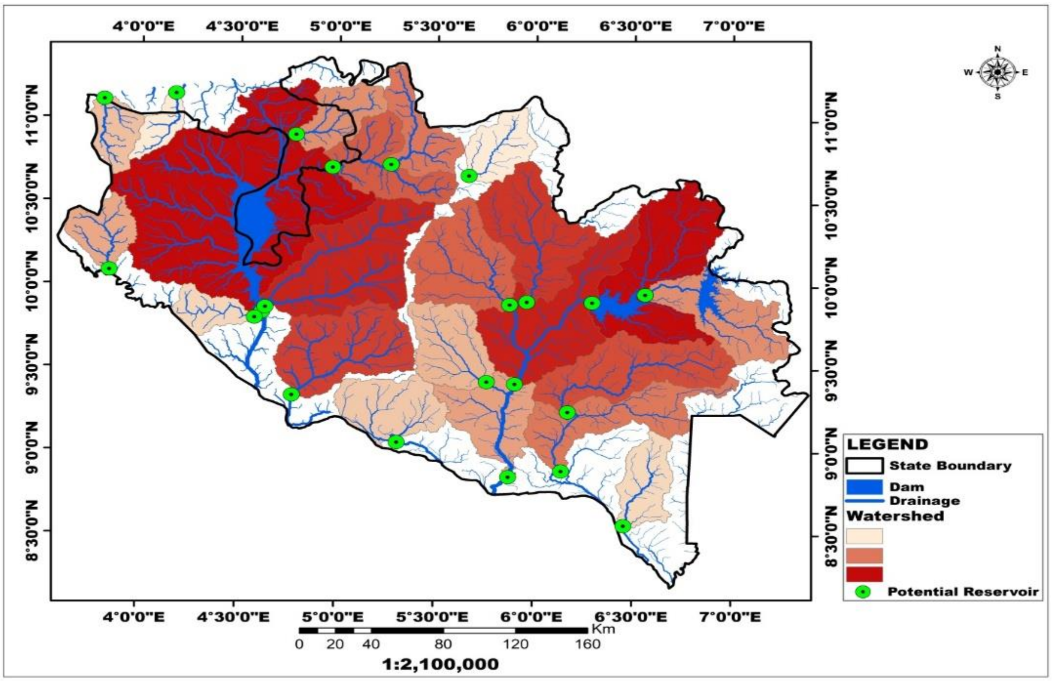

Figure 9: Potential Water Reservoirs for Irrigation Agriculture in Niger State

Watersheds and Potential Water Reservoirs in the Western Part of Niger State

Figure 10 illustrates the geo-hydrological units in the western region of Niger State, showing how water flows downhill through stream networks into rivers and reservoirs. Figure 11 depicts the distribution of natural resources in this region, where agricultural land accounts for more than 80% of the total area. This region contains ten (10) potential water reservoirs for irrigation. Watershed B7 (the Kainji watershed), with geo-hydrological unit code B7, occupies the largest area at 12,358.88 km² (approximately 1.24 million hectares), as shown in Figure 12 and Table 2. The Kainji Dam extends into the southern section of Kebbi State. Watershed

B2, with a geographical extent of 675.77 km² (approximately 67,577 hectares), is the smallest in this region and is designated as a macro-watershed.

The shape of a watershed influences the rate of surface runoff and infiltration within the basin. As shown in Table 2, circularity ratios for this western group range considerably, with Watershed B7 recording a value of 1.553 and Watershed B8 recording 0.556, both lying above the moderate threshold of 0.5. Watersheds with circularity ratios greater than 0.5 exhibit more compact, near-circular shapes, which tend to generate faster and more concentrated runoff, shorter water travel times, and greater susceptibility to flood peaks. In contrast, the majority of watersheds in this region display circularity ratios below 0.4, reflecting elongated, irregular shapes associated with lower runoff intensity and higher infiltration rates. These shape characteristics, combined with the elongated drainage patterns, indicate structural controls likely arising from remnant tectonic structures within the underlying crystalline Basement Complex rocks.

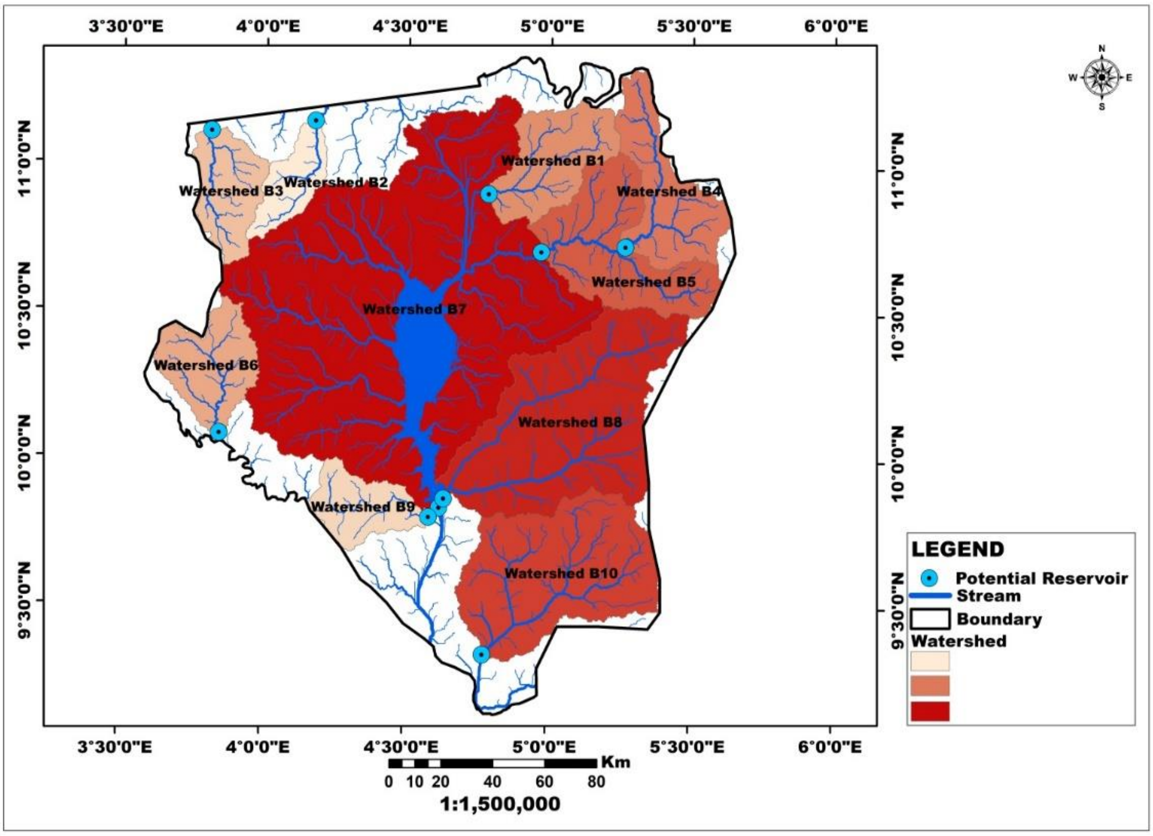

Figure 10: Kainji Dam and Potential Water Reservoirs in the Western Part of Niger State

Table 2: Morphometric Statistics of the Western Watersheds (B-Series)

S/N	Shape Length (m)	Area (km²)	Geohydrological Unit	Circularity Ratio
1	207,992.68	1,385.92	Watershed B1	0.174
2	151,689.27	675.77	Watershed B2	0.085
3	180,605.78	991.83	Watershed B3	0.125
4	281,073.90	1,553.23	Watershed B4	0.195
5	317,270.90	2,183.99	Watershed B5	0.274
6	207,117.28	1,220.77	Watershed B6	0.153

7	717,063.22	12,358.88	Watershed B7	1.553
8	410,609.76	4,427.76	Watershed B8	0.556
9	159,971.40	876.48	Watershed B9	0.110
10	321,508.92	3,356.71	Watershed B10	0.422

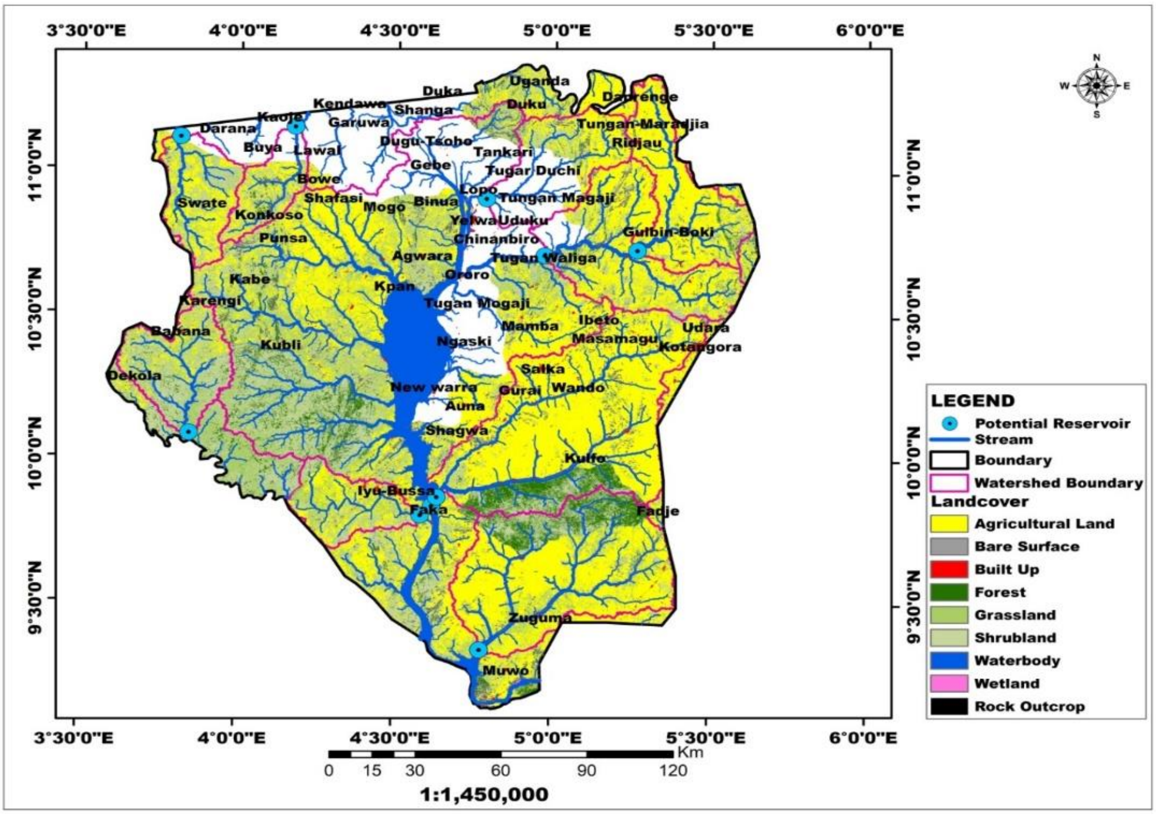

Figure 11: Kainji Dam and its Tributaries, Western Part of Niger State

Watersheds and Potential Water Reservoirs in the Eastern Part of Niger State

Figures 12 and 13 represent the geo-hydrological units in the eastern region of Niger State, showing the flow of water through stream networks into rivers and reservoirs. Figure 14 depicts the distribution of natural resources, with agricultural land again accounting for more than 80% of the total area. This region contains twelve (12) potential water reservoirs for irrigation, labelled A1 to A12 (Figure 14 and Table 3). The watershed size variation is captured through geo-hydrological unit codes (A1–A12 and B1–B10), which are delimited based on hydrological characteristics most relevant to each sub-region. Land use, soil type, geology, topography, and climate are additional factors that characterize each watershed and influence its hydrological behaviour.

The streams in this region display a dendritic network that flows predominantly NE–SW, consistent with the Nigerian regional lineament, confirming structural control over drainage patterns and confirming the role of stream networks as conduits for groundwater recharge. The watershed with geo-hydrological unit code A6 has the largest extent at 4,037.42 km², while Watershed A12 has the smallest extent at 1,414.42 km². The variation in watershed shape is attributed to surface topography, land cover types, climate, geology, and soil characteristics, all of which influence the rates of surface runoff and infiltration within each basin. Two (2) of the twelve (12) watersheds had circularity ratios slightly above 0.5, two (2) had ratios between 0.4 and 0.5, and the remaining seven (7) had ratios below 0.4 (Table 3), consistent with the structurally elongated drainage patterns observed across the study area.

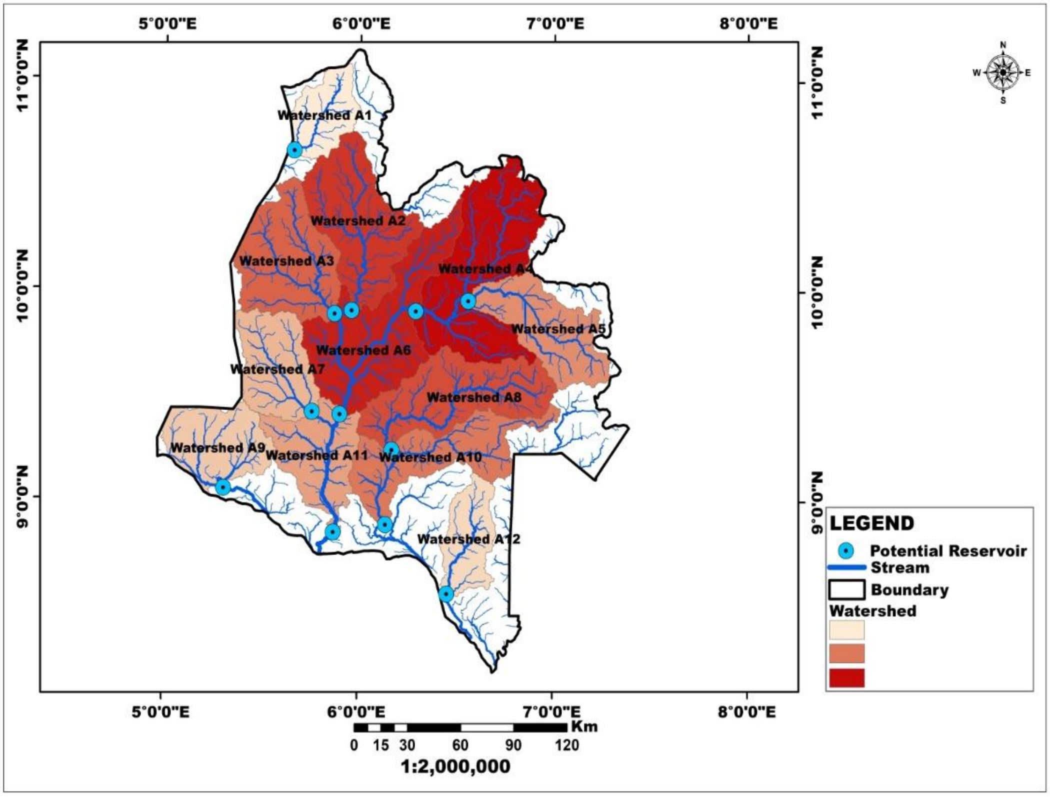

Figure 12: Potential Water Reservoirs in the Eastern Part of Niger State

Table 3: Morphometric Statistics of the Eastern Watersheds (A-Series)

S/No	Shape Length (m)	Area (km²)	Geohydrological Unit	Circularity Ratio
1	187,342.92	1,307.51	Watershed A1	0.164
2	350,460.71	3,294.51	Watershed A2	0.414
3	307,437.26	3,062.49	Watershed A3	0.385
4	498,980.91	4,335.73	Watershed A4	0.545
5	318,658.33	2,455.58	Watershed A5	0.309
6	488,610.36	4,037.42	Watershed A6	0.507
7	248,325.00	2,096.77	Watershed A7	0.264
8	383,412.31	3,292.47	Watershed A8	0.414
9	247,383.82	2,046.55	Watershed A9	0.257
10	460,562.72	2,721.18	Watershed A10	0.342
11	314,448.28	2,131.45	Watershed A11	0.268
12	223,740.10	1,414.42	Watershed A12	0.178

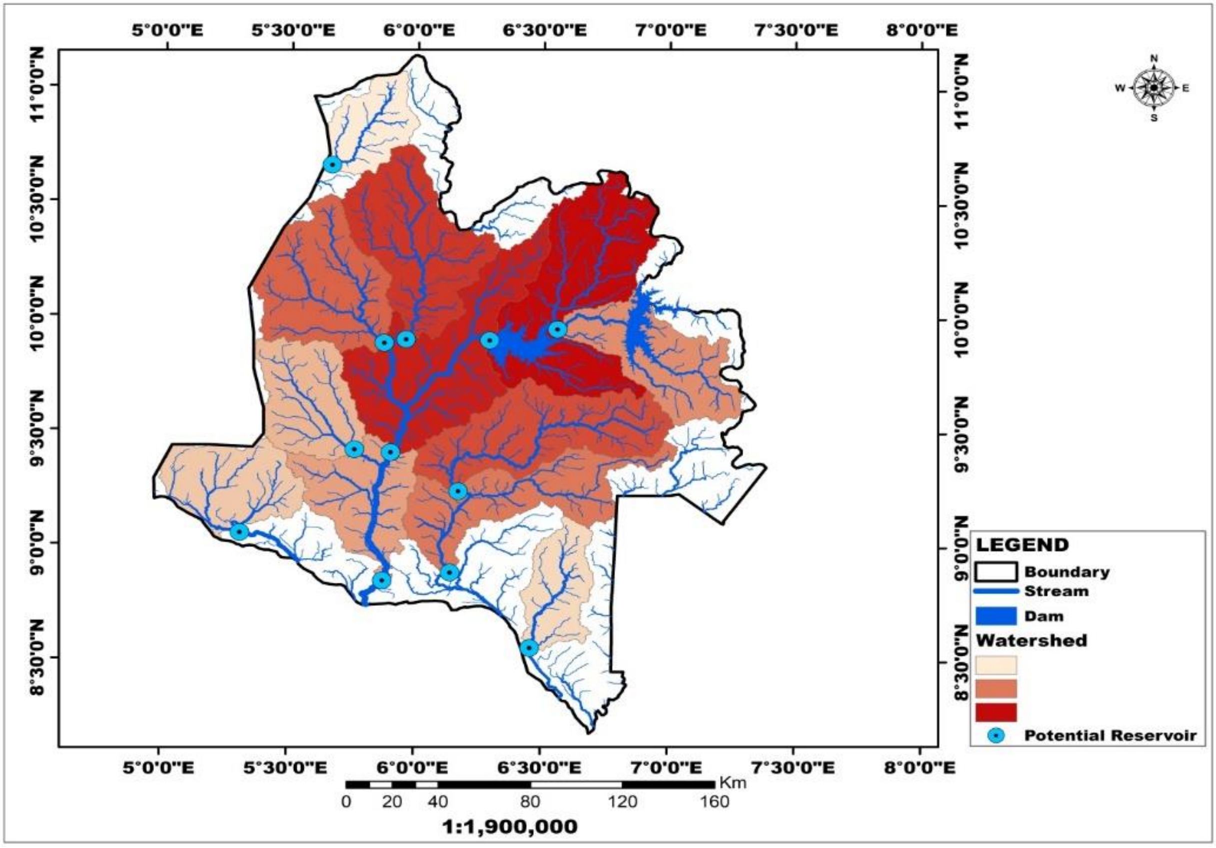

Figure 13: Dams and Potential Water Reservoirs in the Eastern Part of Niger State

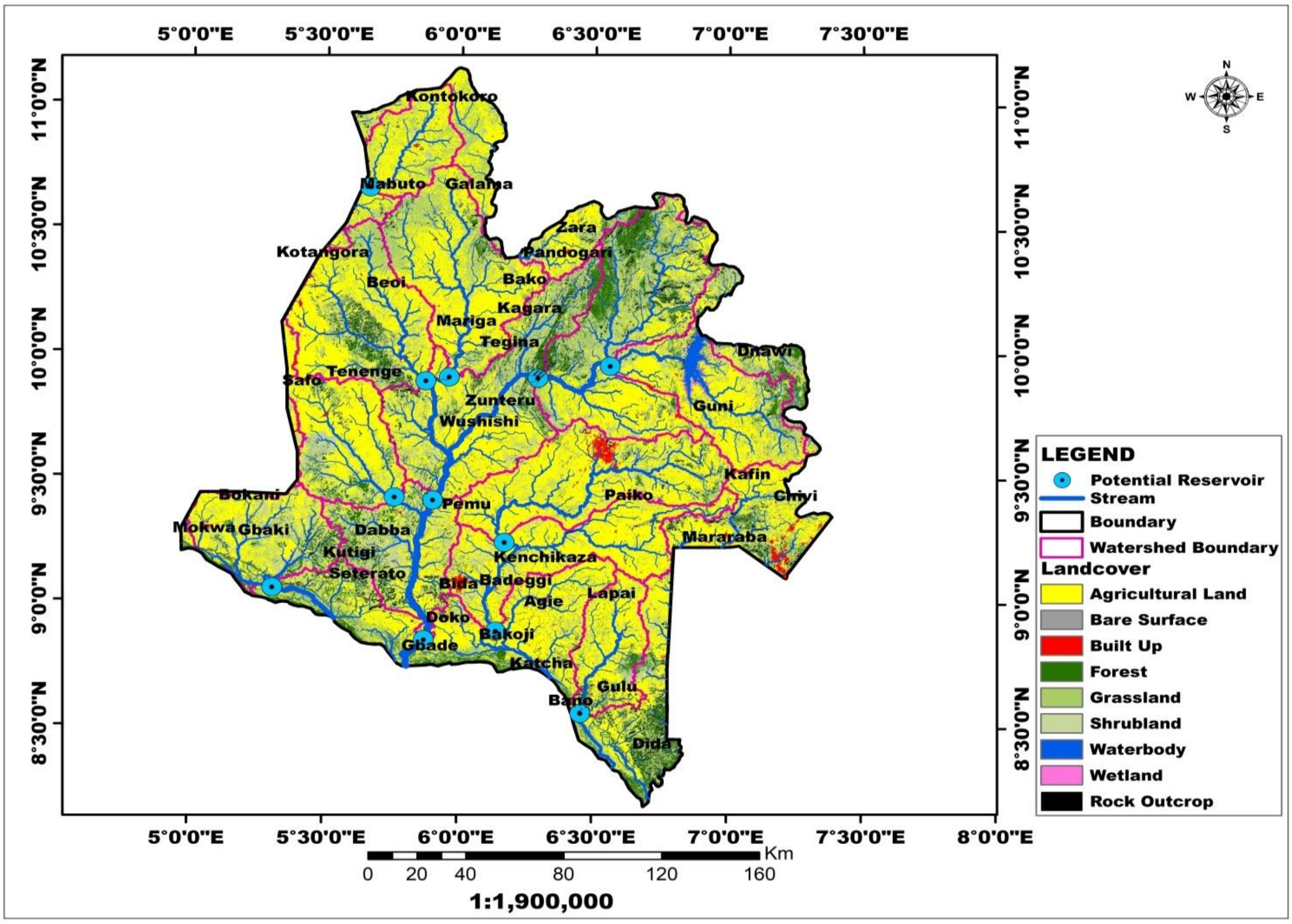

Figure 14: Distribution of Natural Resources in the Eastern Part of Niger State

Hydrological Characteristics of the Shiroro and Zungeru Dam Watersheds

The Shiroro and Zungeru Dam watersheds (Figure 15) comprise six principal hydrological components: (1) the catchment area, defined by the topographic ridgeline that bounds all contributing land; (2) the continuous ridgeline forming the watershed divide; (3) the stream network that collects and routes water from primary and tributary streams to the outlet; (4) the outlet or pour point where discharge is measured; (5) the floodplain adjacent to the primary stream; and (6) the groundwater recharge zones associated with fracture systems in the underlying geology.

The majority of rivers in these watersheds flow in a NE–SW direction, with a minority adopting a SE–NW orientation. The volume of water that drains to the outlet is directly proportional to the size and discharge capacity of the primary stream. Hydrological characteristics are governed by land use, soil types, geology, topography, and climate. The Shiroro Dam is a rock-filled, concrete-faced dam standing 115 meters high and 700 meters in length, with a reservoir holding capacity of approximately 7 billion cubic meters of water, covering a surface area of 34 km². Groundwater recharge is facilitated by the fracture systems in the crystalline basement rocks and by vegetation that intercepts precipitation, reducing surface runoff and promoting infiltration into the groundwater system. Based on stream order analysis, streams in the area can be classified as: influent streams (where streamflow recharges groundwater), effluent streams (where groundwater discharges into streams), perennial streams, intermittent streams, and ephemeral streams (which run only during or immediately after rainfall events).

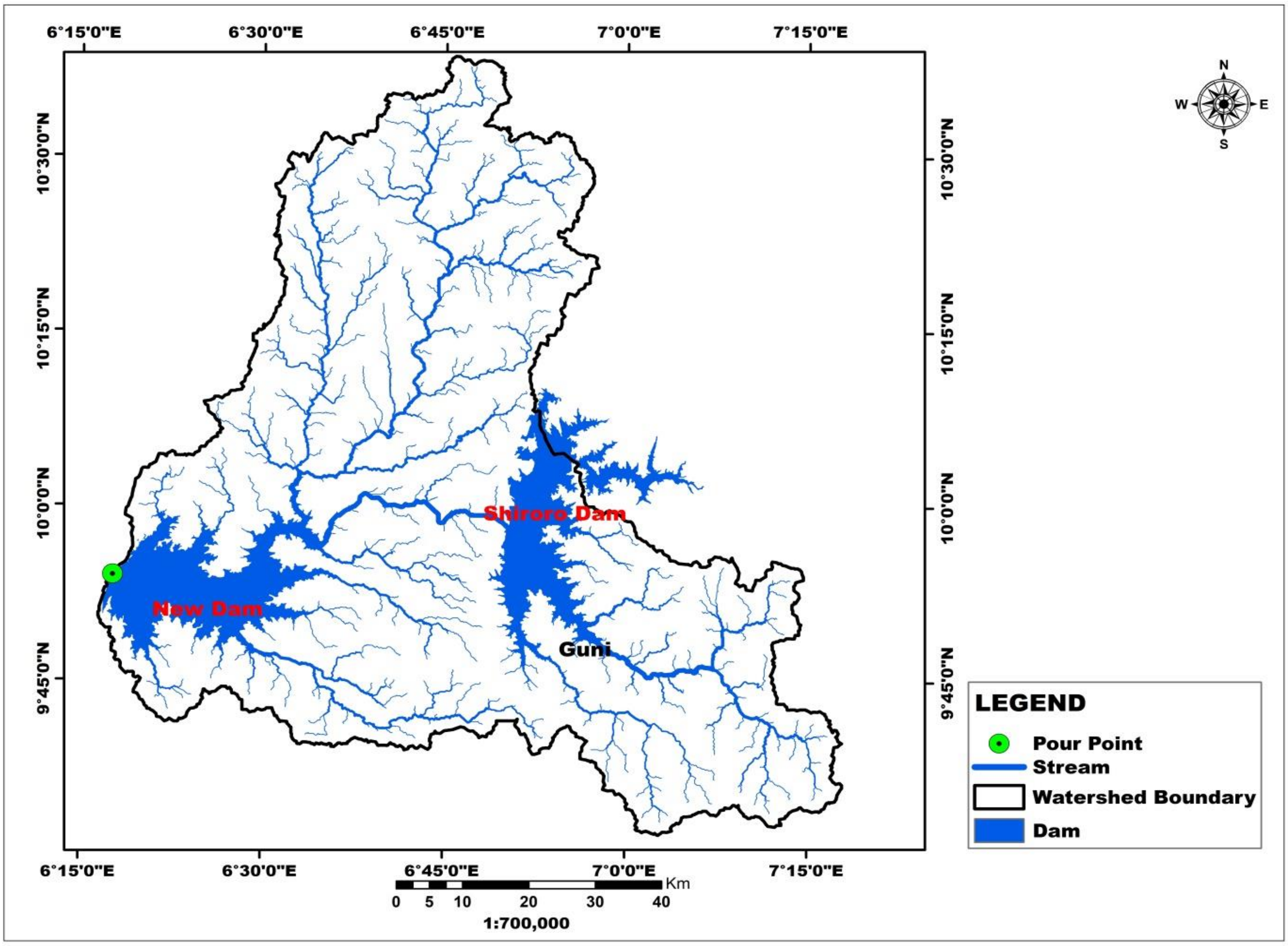

Figure 15: Catchment of Shiroro and Zungeru Dams in Niger State

Spatial Distribution of Natural Resources in the Shiroro and Zungeru Dam Watersheds

Figure 16 and Table 4 present the distribution of land resources and their area coverage within the Shiroro and Zungeru Dam watershed. Agricultural land occupies 2,642.41 km² (264,241 hectares), making it the dominant land cover class. A wetland area of 42.48 km² has potential for rice cultivation. Together, the Shiroro and Zungeru Dams, along with several perennial rivers within the watershed, have the combined capacity to irrigate 2,642.41 km² of cultivated land.

Surface topography exerts a significant influence on stream flow within the watershed. Steep sub-catchments drain rapidly to the main channel, whereas flat terrain produces slower, more uniform drainage responses. Soil properties and the fracture system also regulate stream flow by influencing infiltration rates and baseflow contributions. Vegetation, which varies according to the soil types developed on different rock outcrops, plays a critical role in moderating runoff and promoting groundwater recharge. Since the stream networks are structurally controlled, both surface and groundwater systems are likely to share similar characteristics and orientations, both influenced by geology and topography in the crystalline terrain.

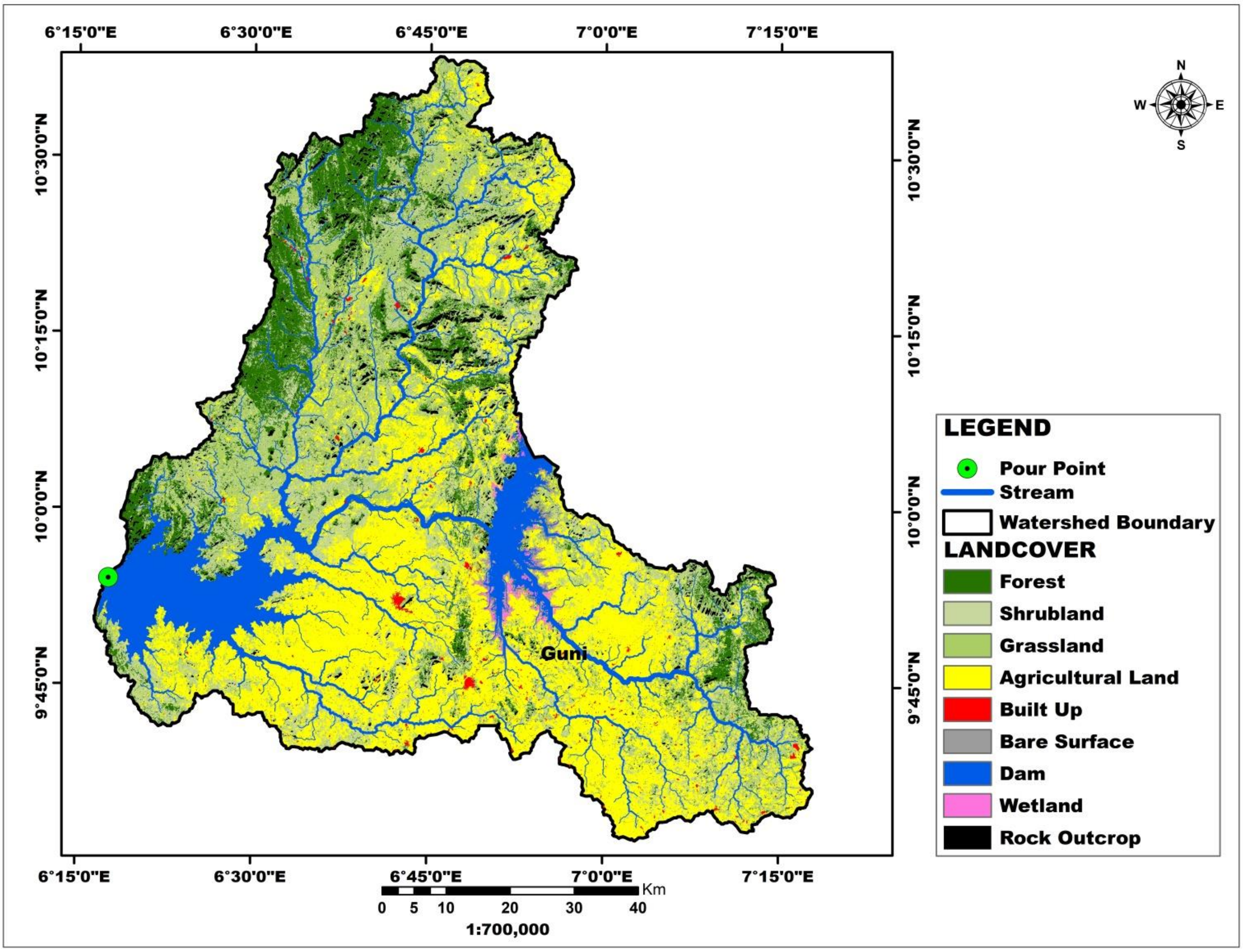

Figure 16: Spatial Distribution of Natural Resources in the Shiroro and Zungeru Dam Watersheds

Table 4: Distribution of Natural Resources in the Shiroro and Zungeru Dam Watershed (km²)

S/N	Land Cover Class	Area (km²)
1	Forest	969.45
2	Shrubland	1,432.16
3	Grassland	1,230.52
4	Agricultural Land	2,642.41

5	Built-up	31.18
6	Bare Surface	44.56
7	Water Bodies	171.10
8	Wetland	42.48

Watersheds Management Plan for Sustainable Irrigation Agriculture

Watershed management is a comprehensive approach to managing land and water resources within a defined geo-hydrological unit. Its goal is the sustainable use and protection of natural resources, balancing ecological, economic, and social needs through integrated land and water resource management, encompassing land, water, vegetation, and socioeconomic dimensions. The management objective is to promote conservation, rehabilitation, and appropriate utilization of natural resources while meeting the aspirations of local communities.

With twenty-two (22) macro-watersheds identified, the management framework proposed for this study adopts a holistic approach that integrates soil and water conservation, afforestation, agronomical best practices, livestock management, renewable energy development, and institutional capacity building to achieve long-term, environmentally sustainable outcomes. The watershed management plan will be guided by the following principles: participatory stakeholder approaches, integrated planning across sectors, management of watersheds as geo-hydrological units, adaptive management in response to monitoring data, and sustainable resource use.

The identification and potential utilization of these watersheds has far-reaching consequences for the surrounding regions. Watersheds that drain directly into the Benue River, in particular, can help mitigate the perennial flooding along its banks, flooding that currently extends westward to the confluence and southward toward the Niger Delta. Controlled damming of these tributaries would provide greater regulation of flow volumes in both the Benue and Niger River systems, offering relief during high-discharge events, particularly when water is released from the Lagdo Dam in Cameroon.

Best practice in integrated watershed management typically includes participatory planning at both landscape and micro scales, drawing on high-quality scientific data from field surveys, geospatial analysis, and earth observation. Watershed planning in the study area should be supported by analytical approaches and the development of a modern knowledge base incorporating existing in-situ data, satellite-derived information, and biophysical surveys. Given the complex hydrological characteristics of the watersheds, a broad multisectoral approach will be essential, including collaboration with agencies such as the World Bank (through the ACReSAL Programme), the Federal Ministry of Water Resources, the Nigerian Hydrological Services Agency, the Integrated Water Resources Management Agency, the Federal Ministry of Environment, and the Niger State Government. Youdeowei et al. (2019) affirmed that effective watershed management requires a careful balance between economic and environmental objectives, supported by a thorough analysis of all biophysical interactions within the watershed system.

Comparative Analysis with Similar Research Studies

The findings of this study are consistent with and complementary to several comparable investigations. Hyungjin Shin et al. (2024) conducted hydrological analysis of watersheds based on water utilization systems using the Catchment Hydrological Analysis Tool (CHAT) model, and identified 27 agricultural reservoir watersheds, a finding broadly consistent with the 22 macro-watersheds delineated in Niger State. Balasubramani (2024) assessed watershed resources for sustainable agricultural development in India using geospatial technologies, applying empirical and quantitative methods to characterize the spatial distribution of watershed resources, highlighting the global relevance of geospatial approaches for water resource planning. Ebenezer et al. (2024) demonstrated significant disparities in access to water sources across agricultural communities in semi-arid Ghana, underscoring the importance of improved water infrastructure such as dams, reservoirs, and river access points, a challenge similarly addressed by the proposed watershed development strategy for Niger State. Furthermore, Jankaro et al. (2023) conducted a GIS-based irrigation suitability evaluation of the Lapai–Agaie Irrigation Scheme in Niger State and found that 59.0% of the evaluated area is highly suitable for irrigation, 32.0% is moderately suitable, and 9.0% is marginally suitable, corroborating the substantial irrigation potential identified in the present study.

SUMMARY OF FINDINGS

1. The study identified twenty-two (22) potential water reservoirs in Niger State, with watershed sizes ranging from 675.77 km² to 12,358.8 km².
2. Geo-hydrological units with a circularity ratio greater than 0.5 exhibit more compact shapes associated with stronger and more concentrated runoff and moderate permeability.
3. More than 55% of watersheds in Niger State have circularity ratios between 0.4 and 0.5, indicative of irregular, elongated shapes with moderate runoff and high permeability.
4. The stream networks display a dendritic pattern flowing predominantly NE–SW, corresponding to the Nigerian regional lineament, confirming structural control and the role of these networks as groundwater recharge conduits.
5. The principal structural control on watershed morphology is attributable to the tectonic tensions that produced the failed triple-arm rifting system, which resulted in the Niger and Benue river valleys and associated sedimentary basins.
6. Niger State has a large agricultural land area of approximately 25,361.27 km² (2.5 million hectares), which is well-positioned for irrigation development given abundant water resources.
7. The prospective water reservoirs identified in this study have the combined capacity to irrigate more than 22,000 km² of agricultural land in Niger State.
8. The Shiroro and Zungeru Dams can irrigate 2,642.41 km² of agricultural land in their combined basin, making a significant contribution to food security.
9. The Kainji Dam watershed, encompassing ten (10) potential macro-watersheds, has the capacity to irrigate approximately 7,000 km² of agricultural land.
10. The Jebba Dam has the potential to irrigate approximately 4,000 km² of agricultural land.

Limitations, Uncertainties, and Future Research Directions

Despite the robustness of the space-based approach employed in this study, several limitations and uncertainties should be acknowledged. The 30-meter spatial resolution of the DEM data may limit the precision of watershed boundary delineation and stream network extraction in areas of gentle or complex terrain. The Land Use/Land Cover classification, while achieving an overall accuracy of 87%, was not validated with ground-truth data in all sub-regions of the state, which may introduce localized classification errors. The MCDA criteria weights, while grounded in established hydrological principles, carry an inherent element of subjectivity and were not subjected to sensitivity analysis, which could affect the ranking of potential reservoir sites.

Furthermore, this study does not incorporate socioeconomic data, such as population density, land tenure, or market access, which are critical for comprehensive watershed management planning. The absence of long-term hydrological monitoring data (stream gauge records, sediment load measurements) limits the quantitative estimation of reservoir storage capacity and irrigation water availability.

Future research should prioritize field-based validation of remotely sensed outputs, including ground-truthing of watershed boundaries and land cover classifications. Integration of socioeconomic data with biophysical datasets through a participatory GIS framework would enhance the relevance and equity of watershed management plans. Sensitivity analysis of the MCDA weights is recommended to assess the robustness of reservoir site rankings. Long-term hydrological monitoring, including installation of stream gauges at key pour points, is essential for calibrating and validating hydrological models, and for tracking changes in watershed behaviour under climate variability and land use change.

CONCLUSION

The advent of space-based technology and its advanced geospatial tools has revolutionized watershed analysis by enabling the acquisition, processing, and interpretation of spatial data at unprecedented scale and resolution. This study demonstrates that a space-based, multi-criteria approach can effectively characterize the hydrological properties of prospective watersheds and dam sites in Niger State, providing a sound data-driven foundation for sustainable irrigation development. The twenty-two macro-watersheds delineated in this study represent substantial, underutilized water resources with the combined potential to irrigate more than 22,000 km² of agricultural land. The sustainable and well-planned utilization of these watersheds can invigorate agricultural activity, increase the state's production of agro-allied products, expand agribusinesses, and ultimately enhance food security in alignment with national development goals.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

- Government agencies and development partners should invest in cutting-edge watershed management systems and irrigation infrastructure to support farming clusters in participating communities, thereby enhancing Nigeria's food security and reducing dependence on imported staple foods.
- A multi-sectoral stakeholder coordination mechanism, involving federal and state water resource agencies, development banks, the private sector, and local communities, should be established to guide the planning, financing, and operation of proposed reservoir and irrigation infrastructure.
- Field validation campaigns should be undertaken to ground-truth the remotely sensed watershed boundaries, land cover classifications, and potential reservoir sites identified in this study, ensuring the accuracy and reliability of subsequent engineering designs.
- Long-term hydrological monitoring networks, including stream gauging stations and rainfall measurement systems, should be established at key locations within the identified watersheds to support model calibration, water balance analysis, and adaptive management.
- Socioeconomic and environmental impact assessments should be integrated into the watershed management planning process to ensure that infrastructure development balances ecological sustainability with the economic and social needs of local communities.
- Watershed-based irrigation development can reduce rural-urban migration by creating economic opportunities within local communities and help mitigate farmer–herder conflicts by reducing pressure on grazing lands and promoting structured land use planning.

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