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Monitoring Spatio-Temporal Changes In Surface Water Bodies In Gombe State, Nigeria Using Landsat And Sentinel-2 Imagery

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Abstract: *Surface water resources in semi-arid environments are highly sensitive to climatic fluctuations and human activities, making long-term monitoring essential for sustainable management. This study evaluated multi-decadal surface water dynamics in Gombe State using satellite-derived Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI) for the years 1987, 2005, 2015, and 2025. Multi-temporal satellite imagery was analyzed to quantify variations in spectral water reflectance and assess temporal trends over 38 years. The results reveal a non-linear pattern of surface water change. In 1987, moderate water presence was observed (NDWI max = 0.36; MNDWI max = 0.48), establishing a baseline condition. A significant increase occurred in 2005 (NDWI = 0.57; MNDWI = 0.96), indicating strengthened water reflectance likely associated with improved rainfall and runoff conditions. In 2015, NDWI declined to 0.30 while MNDWI remained high (0.98), suggesting continued water presence but reduced spectral intensity, possibly due to vegetation interference, turbidity, or seasonal variability. The strongest signal was recorded in 2025 (NDWI = 0.89; MNDWI = 0.99), reflecting substantial enhancement of surface water presence, potentially linked to intense rainfall or flooding events. Across all years, MNDWI demonstrated greater stability and sensitivity than NDWI, confirming its suitability for surface water detection in semi-arid regions. The findings highlight the dynamic and climate-responsive nature of surface water systems and underscore the importance of continuous satellite-based monitoring to support adaptive water resource planning, flood risk management, and drought preparedness in northeastern Nigeria.*

Keywords: *Surface water dynamics; NDWI; MNDWI; Remote sensing; Climate variability; Semi-arid hydrology*

1.0 INTRODUCTION

Surface water bodies including rivers, lakes, reservoirs, and seasonal wetlands—are critical components of natural and human systems, providing essential ecosystem services, supporting agriculture, sustaining biodiversity, and meeting domestic and industrial water demands. In semi-arid and sub-humid regions such as northeastern Nigeria, surface water availability is highly sensitive to climatic variability, land use dynamics, and anthropogenic pressures.

Gombe State experiences a tropical savanna climate characterized by a short but intense wet season and a prolonged dry season. Major water resources such as the Gongola River, Dadin Kowa Reservoir, and numerous seasonal ponds play crucial roles in irrigation, livestock production, fisheries, and floodplain agriculture. However, these water bodies face increasing pressures from population growth, agricultural expansion, dam operations, sedimentation, and climate-induced rainfall variability.

Remote sensing has proven indispensable for monitoring surface water dynamics due to its synoptic coverage, repeat observations, and historical archives. Landsat imagery provided a long-term record of Earth observation data at moderate spatial resolution, enabling change detection from the 1980s onward. Sentinel-2 imagery complemented Landsat data by offering higher spatial resolution (10–20 m) and frequent revisit times, which was particularly useful for detecting small and seasonal water bodies (Du et al., 2016; Nguyen & Le, 2020).

Spectral water indices such as the Normalized Difference Water Index (NDWI) and the Modified NDWI (MNDWI) were effective for delineating water features across diverse environments (Pekel et al., 2016). Integrating these indices with multi-temporal satellite imagery allowed systematic assessment of surface water dynamics at seasonal and inter-annual scales.

1.1 Research Gap

While remote sensing is widely used to monitor surface water in semi-arid regions, long-term studies in smaller Nigerian catchments, such as Gombe State, remain scarce. The effectiveness of NDWI and MNDWI in distinguishing water from dry soil and sparse vegetation under these conditions is also underexplored, and links to climate variability and land use changes are rarely examined. This study addresses these gaps by combining Landsat and Sentinel-2 imagery to assess spatio-temporal changes in surface water and evaluate the reliability of these indices in the region.

1.2 Problem Statement

Surface water resources constitute a critical foundation for agricultural production, domestic water supply, ecosystem sustainability, and flood regulation in semi-arid regions such as Gombe State, northeastern Nigeria. Despite their socio-economic and environmental significance, systematic, spatially explicit, and quantitative information on the extent and dynamics of surface water bodies within the state remained limited. Existing studies and administrative records were often fragmented, outdated, or based on localized field surveys that failed to capture long-term trends and spatial variability across the landscape.

Rapid population growth, expansion of rain-fed and irrigated agriculture, urban development, and increasing climate variability have intensified pressures on surface water resources in the region. Changes in rainfall patterns, coupled with land use and land cover modifications, altered the distribution, persistence, and seasonal behavior of rivers, reservoirs, and ephemeral water bodies. These changes were poorly documented, constraining the ability of policymakers and resource managers to respond effectively to emerging water-related challenges (Pekel et al., 2016; Gashu & Alemayehu, 2019).

The lack of reliable, multi-temporal, and spatially continuous data on surface water dynamics limited effective water resource management, flood risk mitigation, and agricultural planning in Gombe State. Satellite remote sensing provided a practical solution by enabling consistent, cost-effective, and long-term monitoring of surface water at regional scales. In particular, the integration of Landsat and Sentinel-2 imagery allowed assessment of both historical and recent changes in surface water extent with sufficient spatial and temporal resolution.

1.3 Aim and Objectives

1.3.1 General Objective

This study monitored and quantified spatio-temporal changes in surface water bodies in Gombe State using multi-temporal Landsat and Sentinel-2 satellite imagery.

1.3.2 Specific Objectives

1. Multi-temporal Landsat and Sentinel-2 imagery covering Gombe State were acquired and compiled.
2. Satellite imagery was preprocessed through atmospheric correction, cloud masking, and geometric alignment.
3. Surface water features were extracted using NDWI and MNDWI spectral indices.
4. Change detection analyses were conducted to quantify expansion, contraction, and seasonal variability of water bodies.
5. Observed changes were interpreted in relation to climate variability and land use/land cover dynamics.

1.4 Significance of the Study

The study provided reliable, spatially explicit information on the distribution and dynamics of surface water bodies in Gombe State, supporting evidence-based water resource management and sustainable development planning. By mapping seasonal and long-term changes in rivers, reservoirs, and ephemeral water bodies, the findings enhanced agricultural planning, improved irrigation and dry-season farming strategies, and contributed to food security. The results also informed flood risk assessment and climate change adaptation by identifying areas prone to seasonal inundation and water scarcity. Additionally, the study generated valuable geospatial datasets and a replicable remote sensing framework that can support land-use planning, environmental protection, and policy formulation in Gombe State and similar semi-arid regions.

2.0 METHODOLOGY

2.1 Study Area

Gombe State is located in northeastern Nigeria between latitudes approximately 9°30′ and 11°15′ N and longitudes 10°15′ and 11°30′ E. The state covers an estimated land area of about 20,265 km² and shares boundaries with Borno State to the east, Yobe State to the north, Bauchi State to the west, and Adamawa State to the south (Udoh, 1970). Gombe State lies largely within the Gongola River Basin, a major sub-basin of the Upper Benue River system, making surface water resources a defining feature of its physical environment (FAO, 2018).

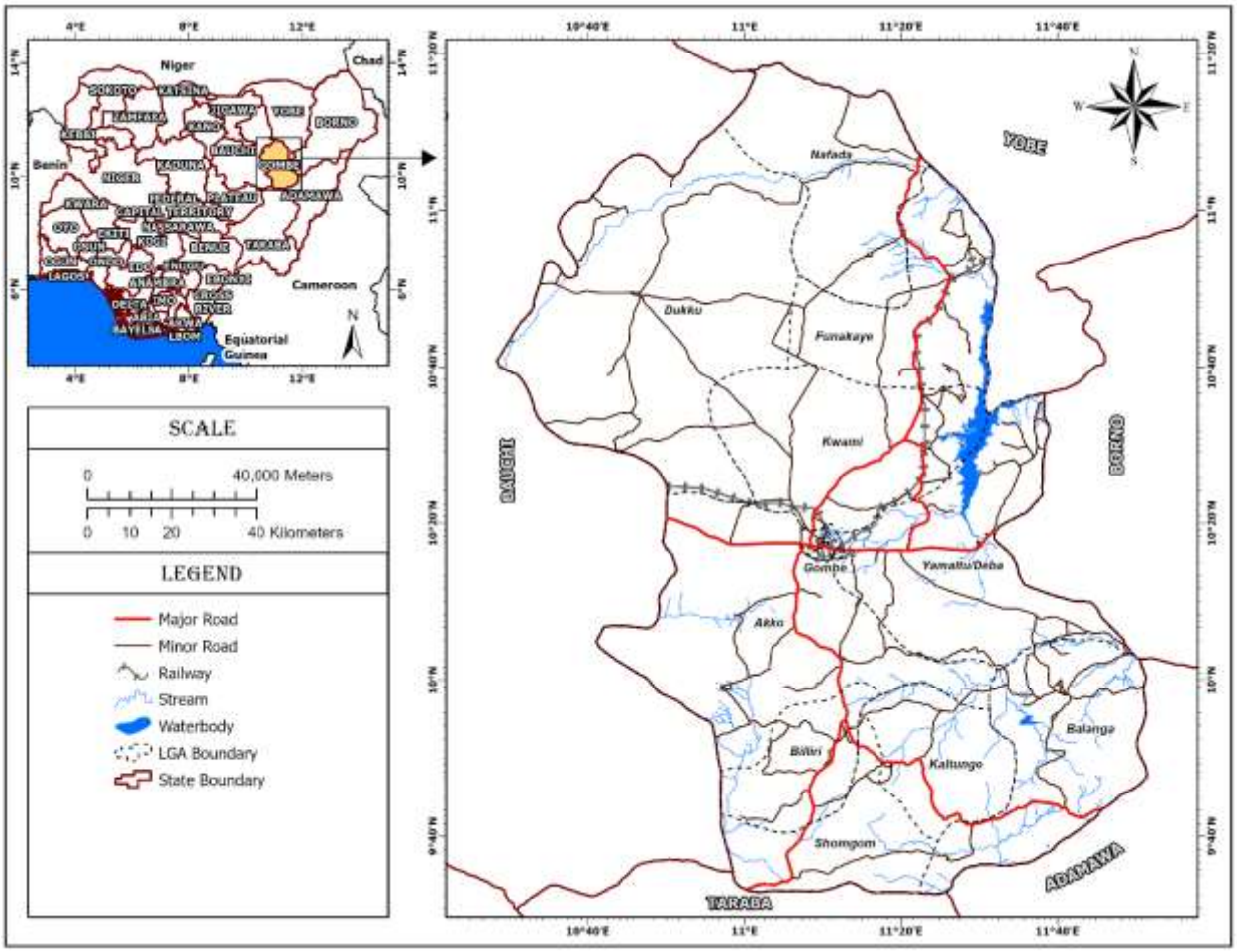

Figure 1 : Map of the Study Area

2.1 Climate, Geology, and Environment

Gombe State experiences a tropical savanna (Aw) climate characterized by a rainy season from May to September and a dry season from October to April. This pattern is largely shaped by the movement of the Inter-Tropical Convergence Zone (ITCZ) and the influence of the Harmattan winds. Annual precipitation ranges between 850 and 1,100 mm, decreasing toward the northern parts of the state. These rainfall patterns significantly affect river flows, reservoir levels, and temporary wetlands, which in turn influence agricultural productivity and the risk of flooding and droughts.

Geologically, the state is situated within the Upper Benue Trough, dominated by sedimentary rock formations including sandstones, shales, siltstones, and limestone. Notable formations such as the Gombe Sandstone and the Pindiga Formation play a key role in groundwater replenishment, surface runoff, and soil development. Soils are primarily ferruginous tropical types, ranging from sandy loams on uplands to fertile alluvial soils along riverbanks and reservoirs, which support both irrigated and dry-season farming.

The landscape features gently rolling plains with occasional hills rising between 300 and 800 meters, gradually sloping toward the Gongola River system. The Gongola River, regulated by the Dadin Kowa Dam, is the main drainage channel, supplemented by seasonal streams and ephemeral waterways. Low-lying areas along these waterways are vulnerable to seasonal flooding.

Vegetation is typical of the Sudan and Northern Guinea savanna zones, dominated by grasses with scattered trees and shrubs such as Acacia, Isoberlinia, and Parkia. Riparian areas support denser vegetation. Human activities, including farming expansion, fuelwood collection, and urbanization, have altered the natural vegetation cover, impacting runoff patterns and surface water availability.

The state's economy is predominantly agricultural, with both rain-fed and irrigated crops like maize, millet, sorghum, rice, groundnuts, and vegetables forming the backbone of livelihoods. Livestock rearing, fishing, and small-scale trade also play

important roles. The heavy reliance on surface water resources for farming, domestic use, and livestock highlights the importance of monitoring water availability to ensure food security and sustainable development.

2.2 Types and Sources of Data

Table 1: Types and Sources of Data

YEAR	TYPE	SOURCES	BANDS	RESOLUTION
1987	Landsat 5 ETM+	USGS Earth Explorer platform	Band 2 (Green) Band 4 (NIR) Band 5(SWIR1)	30m resampled to 10m 30m resampled to 10m 30m resampled to 10m
2005	Landsat 7 ETM+	USGS Earth Explorer platform	Band 2 (Green) Band 4 (NIR) Band 5(SWIR1)	30m resampled to 10m 30m resampled to 10m 30m resampled to 10m
2015	Sentinel-2 Level-1C (atmospheric corrected to Sentinel-2 Level-2A)	ESA Copernicus Open Access Hub	Band 3 (Green) Band 8 (NIR) Band 11 (SWIR1)	10m 10m 20m resampled to 10m
2025	Sentinel-2 Level-2A	ESA Copernicus Open Access Hub	Band 3 (Green) Band 8 (NIR) Band 11 (SWIR1)	10m 10m 20m resampled to 10m

2.3 Image Preprocessing and Surface Water Extraction

Multi-temporal Landsat and Sentinel-2 imagery were acquired for the study period (1987–2025) and subset to the administrative boundaries of Gombe State to focus the analysis on the study area and reduce computational load. Prior to analysis, the imagery underwent several preprocessing steps to ensure consistency and accuracy in detecting surface water dynamics.

Radiometric and atmospheric corrections were first applied to convert raw digital numbers (DNs) to surface reflectance, accounting for sensor calibration, atmospheric scattering, and absorption. Landsat images were converted to top-of-atmosphere reflectance using sensor-specific calibration coefficients, followed by atmospheric adjustment using the Dark Object Subtraction (DOS) method. Sentinel-2 imagery was processed with the Sen2Cor atmospheric correction tool to generate bottom-of-atmosphere reflectance products.

Next, cloud and cloud-shadow masking was conducted to remove pixels obscured by clouds or their shadows, which could interfere with water detection. Landsat images were processed using the Fmask algorithm, while Sentinel-2 imagery relied on quality assurance (QA) bands to identify and exclude cloud-affected pixels. This ensured that only valid, cloud-free pixels were used for subsequent analysis.

Geometric correction and reprojection were then applied to all images to align them to a common coordinate reference system (WGS84/UTM Zone 32N), correcting for sensor distortions and terrain-induced misalignments. This step ensured accurate pixel-to-pixel comparison across multiple years, which is critical for robust multi-temporal change detection.

Following preprocessing, surface water extraction was performed using spectral water indices, which enhance water reflectance relative to surrounding land, vegetation, and built-up areas:

NDWI = (Green – NIR) / (Green + NIR)

MNDWI = (Green – SWIR) / (Green + SWIR)

These indices were calculated for each image, and multi-temporal NDWI and MNDWI maps were generated for the years 1987, 2005, 2015, and 2025. The resulting maps were analyzed to quantify surface water expansion, contraction, and seasonal variability over the study period, providing a reliable basis for assessing hydrological patterns and land use dynamics in Gombe State.

2.4 Tools and Software

The study utilized the following tools:

- **ArcGIS Pro version 3.4 for** spatial analysis and map production.

3.0 RESULTS AND DISCUSSION

3.1 Results of Surface Water Analysis (1987–2025)

This section presents the results of surface water extraction in Gombe State using NDWI and MNDWI derived from satellite imagery for 1987, 2005, 2015, and 2025. The values represent the spectral strength of surface water presence across the study area.

Higher positive values indicate stronger water reflectance, while negative values represent non-water surfaces such as dry soil, vegetation, or built-up areas.

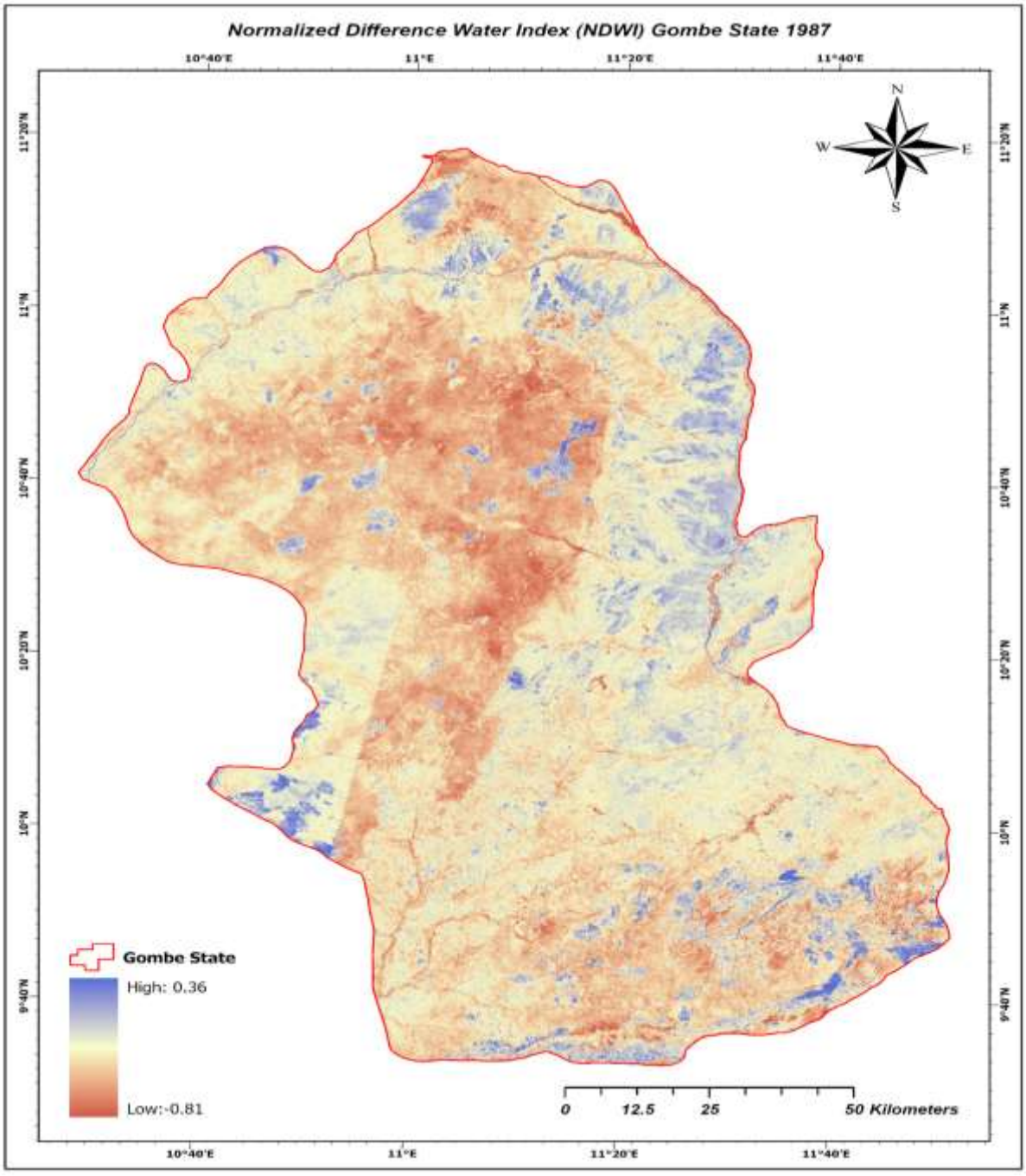

Figure 2: 1987 NDWI of the Study Area

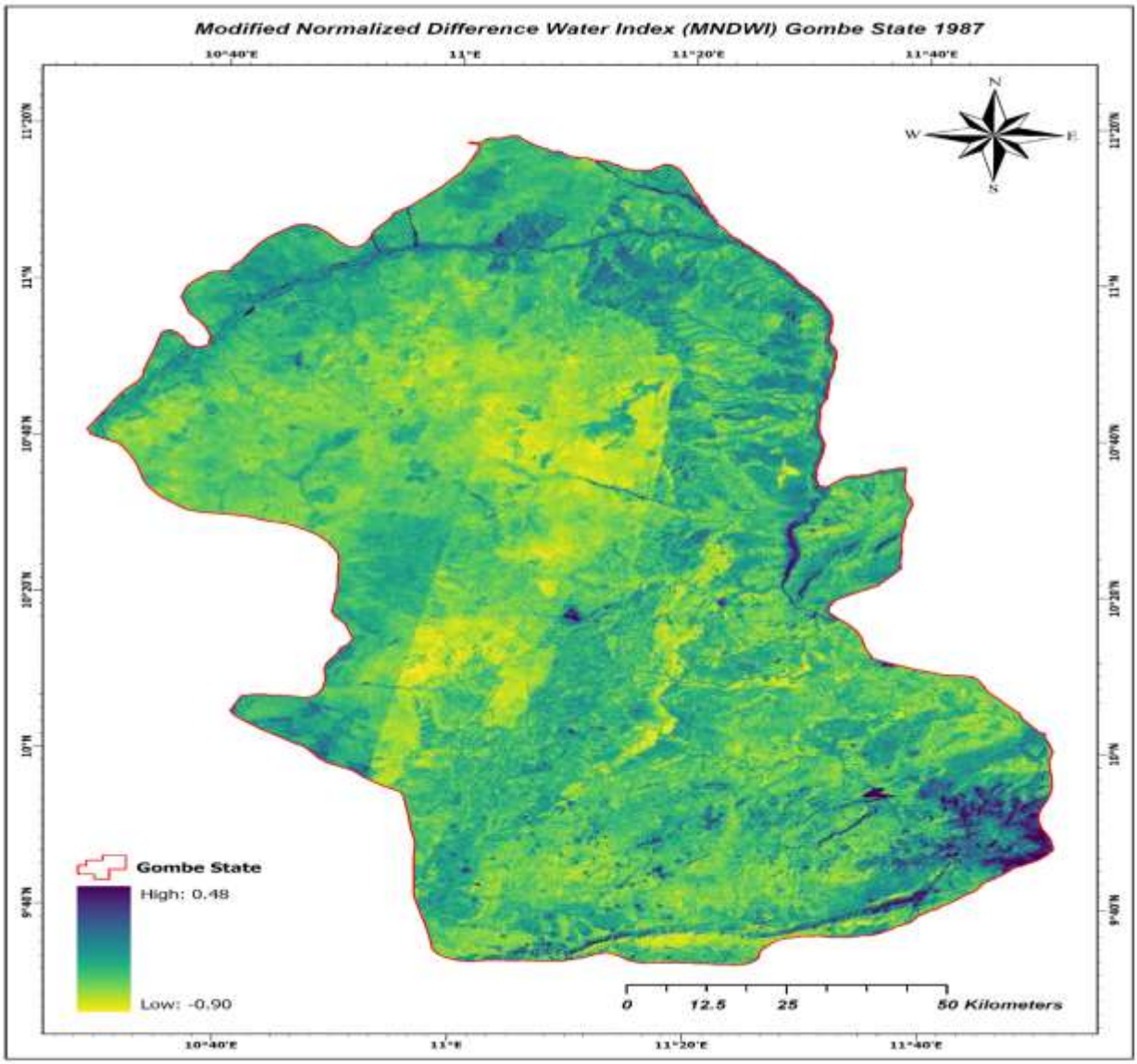

Figure 3: 1987 MNDWI of the Study Area

3.2 Year-by-Year Results

3.2.1 Surface Water Condition in 1987

Table 2: Surface Water Condition in 1987

Index	Minimum	Maximum
NDWI	-0.81	0.36
MNDWI	-0.90	0.48

The 1987 results indicate moderate surface water presence across the state. The maximum NDWI value of 0.36 suggests detectable but not extensive water bodies. MNDWI recorded a slightly higher maximum (0.48), indicating improved water separation compared to NDWI.

The strong negative minimum values confirm that large portions of the state were dominated by dry land and sparse vegetation, consistent with semi-arid environmental conditions.

This year serves as the baseline for evaluating subsequent changes.

3.2.2 Surface Water Condition in 2005

Table 3: Surface Water Condition in 2005

Index	Minimum	Maximum
NDWI	-0.76	0.57
MNDWI	-0.68	0.96

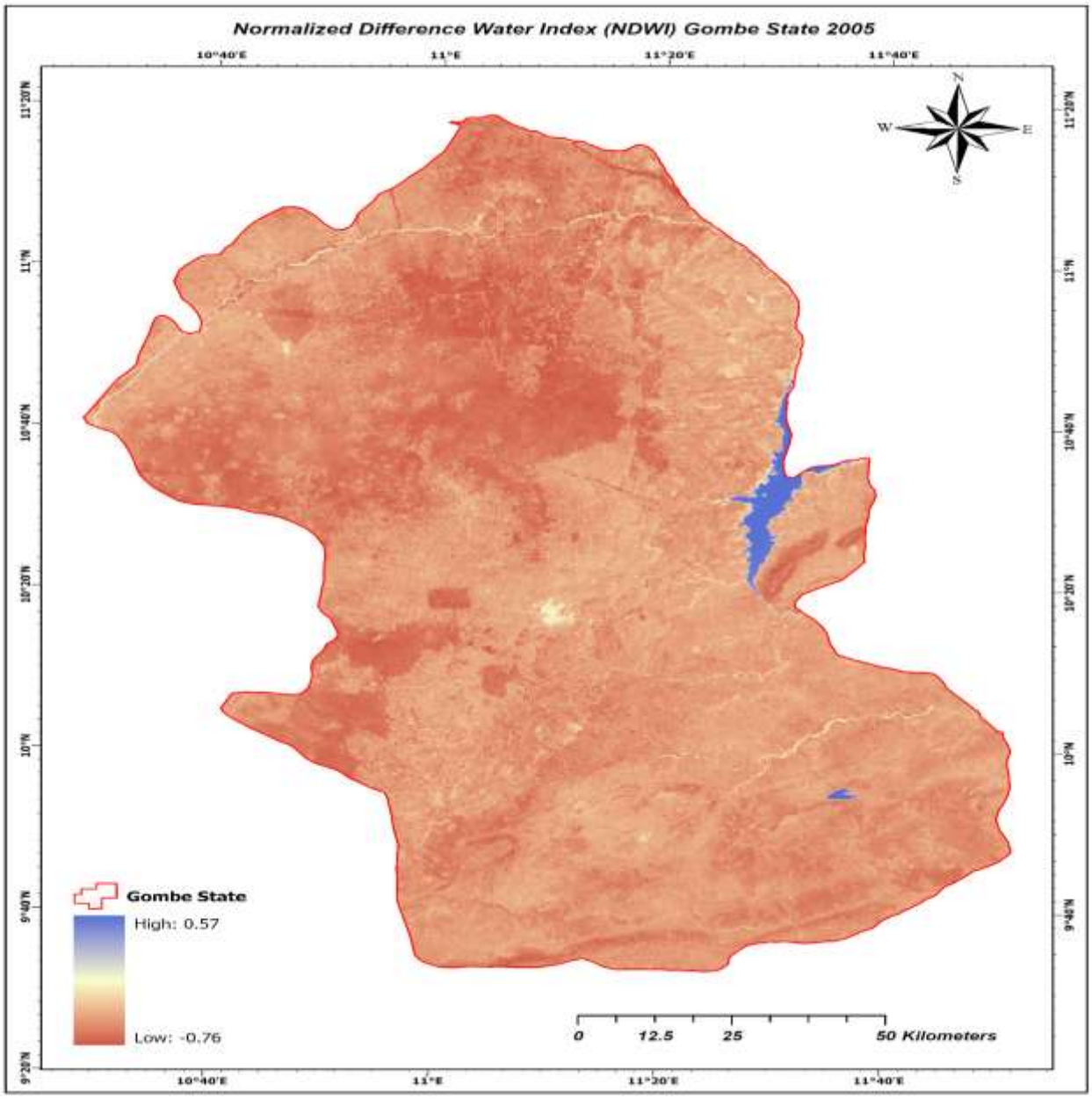

Figure 4: 2005 NDWI of the Study Area

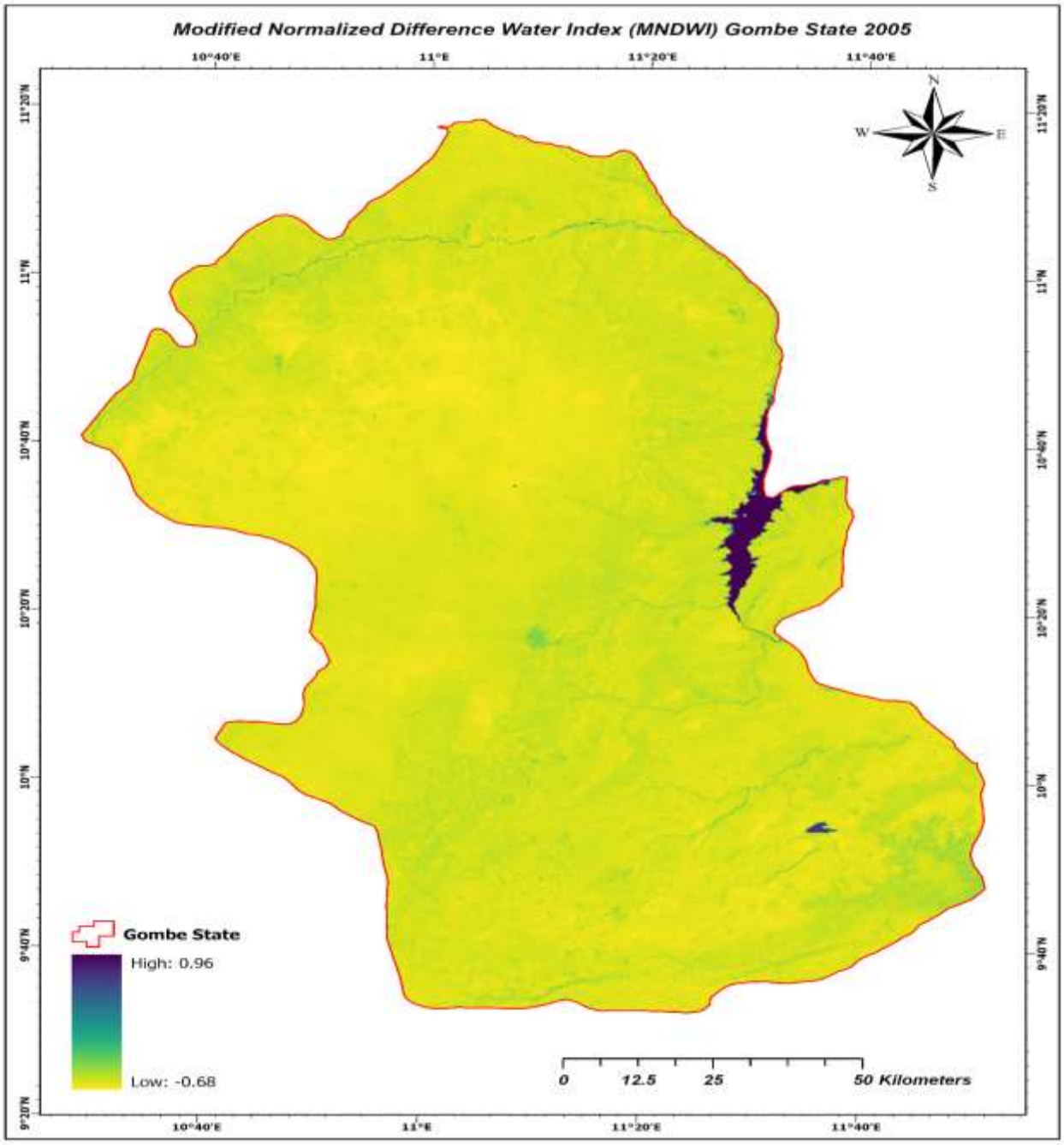

Figure 5: 2005 MNDWI of the Study Area

In 2005, both indices show a clear increase in water signal intensity compared to 1987.

- NDWI increased from 0.36 to 0.57.
- MNDWI rose sharply from 0.48 to 0.96.

The significant rise in MNDWI indicates stronger open water reflectance and improved separation from surrounding land features. This suggests either increased water volume, clearer water surfaces, or expanded water coverage during the period.

Overall, 2005 reflects a notable enhancement in surface water presence relative to the baseline year.

3.2.3 Surface Water Condition in 2015

Table 4: Surface Water Condition in 2015

Index	Minimum	Maximum
NDWI	-1.00	0.30
MNDWI	-0.60	0.98

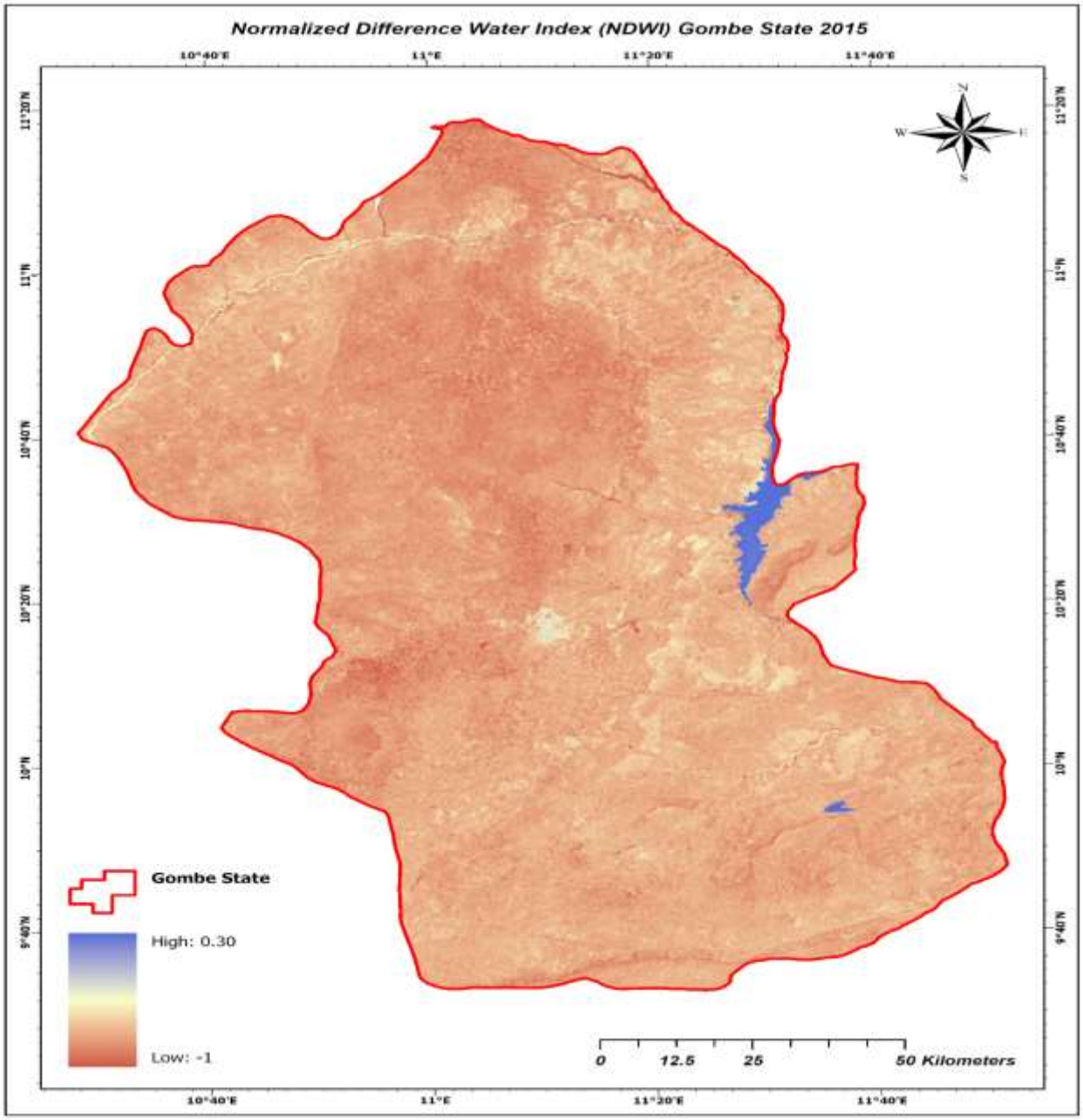

Figure 6: 2015 NDWI of the Study Area

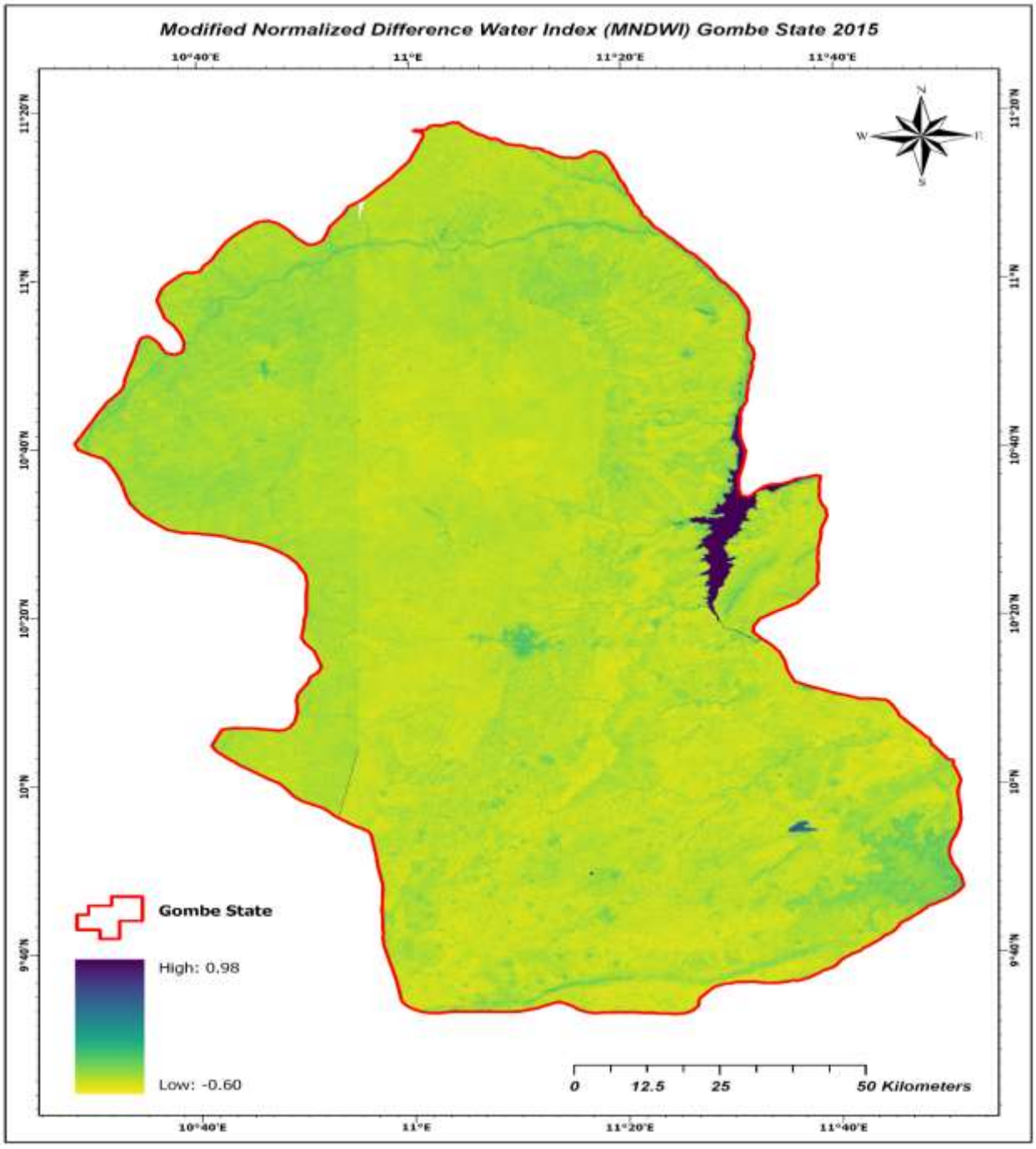

Figure 7: 2015 MNDWI of the Study Area

The 2015 results show contrasting behavior between the two indices.

- NDWI decreased significantly from 0.57 (2005) to 0.30.
- MNDWI remained very strong at 0.98.

The drop in NDWI suggests reduced water reflectance intensity or possible spectral interference from vegetation or turbidity. However, the high MNDWI value confirms that water bodies were still present and clearly detectable.

This indicates a temporary weakening in NDWI-based water signal but continued strong detection under MNDWI.

3.2.4 Surface Water Condition in 2025

Table 5: Surface Water Condition in 2025

Index	Minimum	Maximum
NDWI	-0.99	0.89
MNDWI	-0.57	0.99

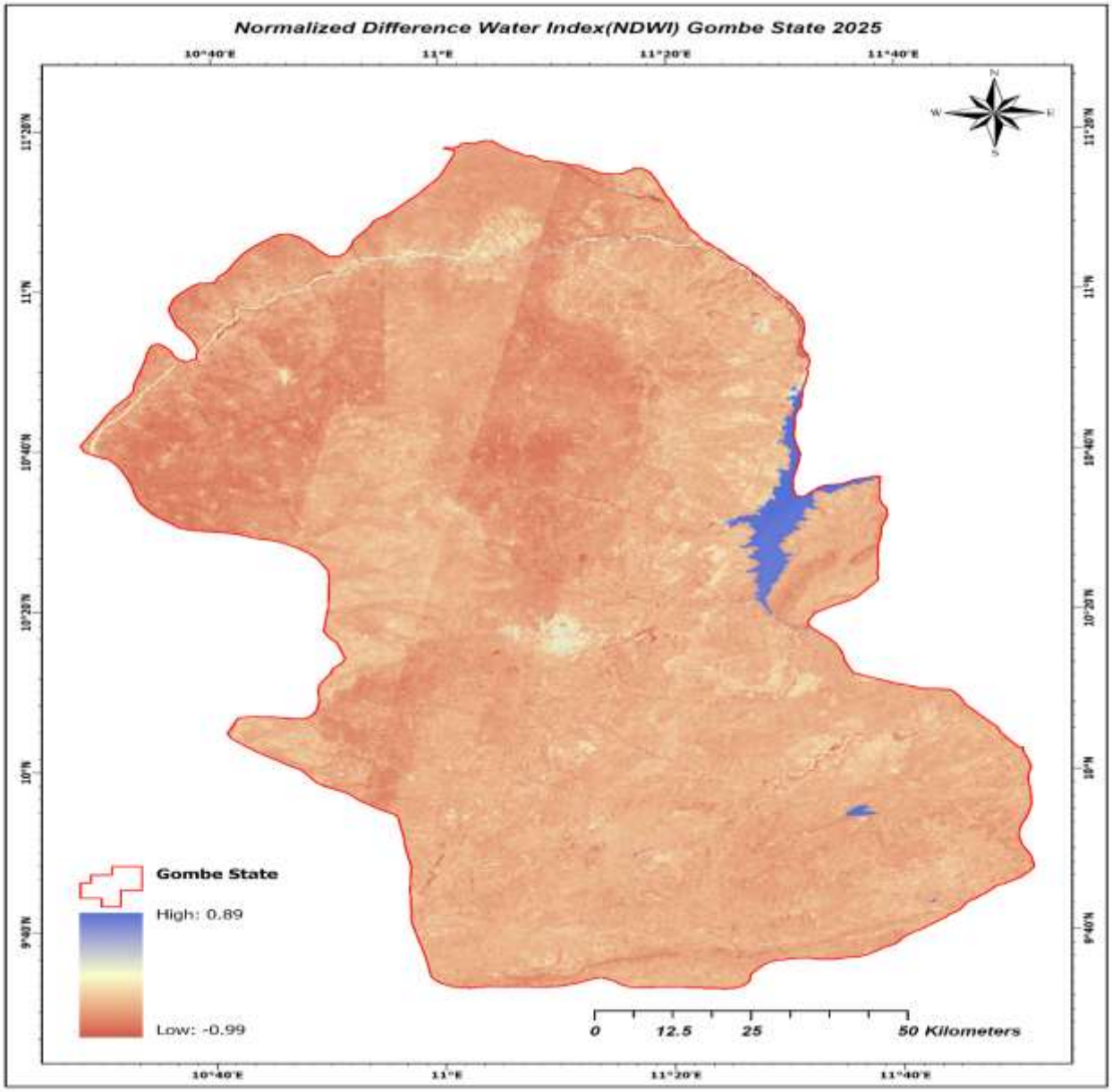

Figure 8: 2025 NDWI of the Study Area

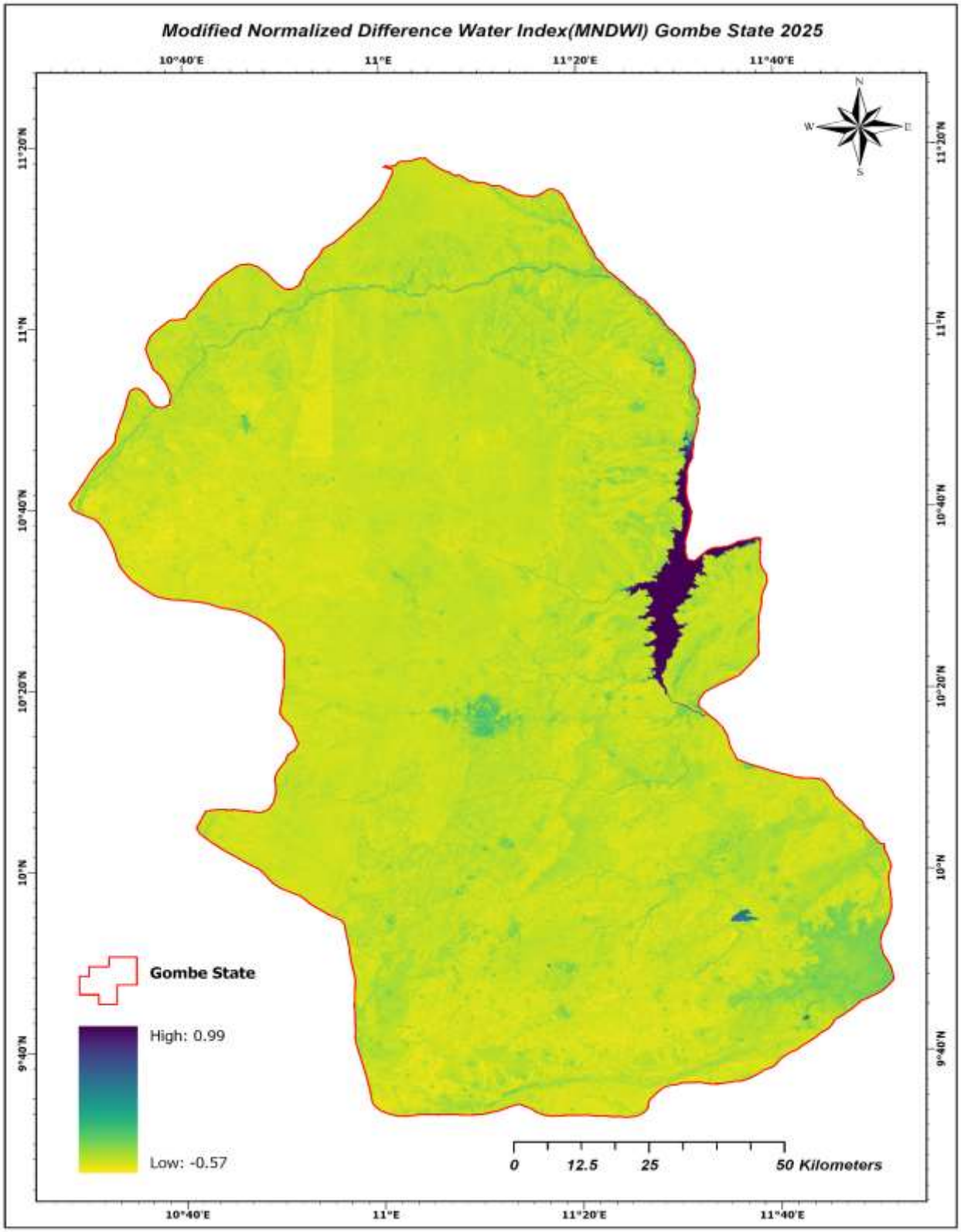

Figure 9: 2025 MNDWI of the Study Area

The 2025 results record the highest water signal across all years analyzed.

- NDWI increased sharply from 0.30 (2015) to 0.89.

- MNDWI reached 0.99, the highest value observed in the study.

These results indicate very strong surface water reflectance and clear spectral distinction between water and non-water surfaces.

Among the four years, 2025 represents the peak of water detection intensity.

3.3 Temporal Trend Analysis

The long-term pattern of surface water changes from 1987 to 2025 reveals a non-linear trend.

1987 → 2005

- NDWI increased by +0.21
- MNDWI increased by +0.48

This phase reflects a clear strengthening of surface water presence.

2005 → 2015

- NDWI decreased by -0.27
- MNDWI remained relatively stable (+0.02)

This phase indicates temporary reduction in NDWI signal while MNDWI maintained strong detection.

2015 → 2025

- NDWI increased sharply by +0.59
- MNDWI reached peak performance

This phase reflects a strong resurgence of surface water intensity.

Overall Pattern (1987–2025)

The results show three main phases:

1. **Increase Phase (1987–2005)**
2. **Temporary Decline Phase (2005–2015)**
3. **Strong Expansion Phase (2015–2025)**

Across all years, MNDWI consistently produced stronger and more stable water detection than NDWI, confirming its higher reliability in semi-arid environments such as Gombe State.

3.4 Implications of the Observed Changes

The fluctuations observed over nearly four decades have important environmental, economic, and social implications for Gombe State.

3.4.1 Climate Sensitivity

The strong variation in index values suggests that surface water in the state is highly sensitive to rainfall variability and broader climate dynamics. Periods of increase may reflect wetter climatic conditions, while declines may correspond to drier phases or shorter rainy seasons.

3.4.2 Agricultural Implications

Surface water directly supports irrigation farming.

- Increased water presence (e.g., 2005 and 2025) may enhance agricultural productivity.
- Reduced intensity (e.g., 2015) may lead to irrigation stress and reduced crop yields.

The water variability may affect farmers and influences food security in the state.

3.4.3 Flood and Drought Risk

The sharp increase in 2025 suggests possible elevated flood risk, particularly in low-lying or rapidly urbanizing areas. Conversely, periods of reduced water intensity may signal increased drought vulnerability.

Serious measures need to be put in place by the state ministry of water resources, environment and all other stakeholders to avert flood risk and displacement of communities.

3.4.4 Urban and Infrastructure Impact

Urban expansion can influence runoff patterns and water accumulation. Strong water signals in later years may partly reflect increased surface runoff due to impervious surfaces.

Unplanned urban growth may therefore increase flood exposure. The town planners, urban development and key actors should give wider publicity to the inhabitants on the risk of building on water ways.

3.4.5 Environmental and Ecosystem Effects

Fluctuating water levels affect wetlands, aquatic biodiversity, and ecosystem stability. Periods of contraction may stress aquatic habitats, while expansion phases may temporarily enhance ecosystem productivity.

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study evaluated long-term surface water variability in Gombe State using multi-temporal satellite imagery and two widely applied water indices: The Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI). By analyzing data from 1987, 2005, 2015, and 2025, the study provided a nearly four-decade perspective on hydrological dynamics in a semi-arid environment.

The findings reveal that surface water distribution in the study area exhibits a non-linear and climate-sensitive pattern. In 1987, surface water presence was moderate, with NDWI and MNDWI maximum values of 0.36 and 0.48, respectively. This year serves as the baseline condition for assessing subsequent changes. A clear increase in water reflectance was observed in 2005, with NDWI rising to 0.57 and MNDWI to 0.96, indicating strengthened surface water presence. This phase likely reflects improved rainfall conditions and enhanced runoff accumulation.

In contrast, 2015 recorded a decline in NDWI (0.30), although MNDWI remained high (0.98). This divergence suggests that while water bodies persisted, spectral interference from vegetation, turbidity, or seasonal variability may have reduced NDWI sensitivity. The results indicate a temporary weakening of water signal intensity rather than a complete disappearance of water bodies.

The most significant increase occurred in 2025, when NDWI reached 0.89 and MNDWI peaked at 0.99—the highest values recorded during the study period. These findings suggest substantial enhancement of surface water reflectance, potentially associated with intense rainfall events, increased runoff, or seasonal peak water levels.

Overall, the temporal pattern can be summarized in three phases: (1) hydrological strengthening between 1987 and 2005, (2) temporary decline between 2005 and 2015, and (3) strong resurgence between 2015 and 2025. The results clearly demonstrate that surface water dynamics in Gombe State are highly variable and responsive to both climatic fluctuations and anthropogenic influences.

Importantly, MNDWI consistently outperformed NDWI across all years, confirming its greater robustness for surface water detection in semi-arid regions where vegetation and built-up areas may interfere with traditional indices. The study therefore reinforces the suitability of MNDWI as a reliable tool for long-term water monitoring in similar environmental settings.

4.2 Implications

The observed variability in surface water has significant environmental, socioeconomic, and planning implications for Gombe State.

First, the fluctuations highlight the strong sensitivity of surface water resources to rainfall variability and broader climate dynamics. Periods of reduced water intensity may increase drought vulnerability, affecting agriculture, domestic water supply, and ecosystem stability. Conversely, periods of strong water expansion—such as observed in 2025—may increase flood risks, particularly in low-lying and rapidly urbanizing areas.

Second, agricultural productivity in the state is closely linked to surface water availability. Increased water presence can enhance irrigation potential and crop yields, while reduced intensity may intensify water competition and pressure on groundwater resources.

Third, expanding urban areas may alter natural drainage patterns and increase surface runoff, potentially amplifying flood risks during high-rainfall periods. The interaction between climate variability and land use change therefore represents a critical factor influencing future water resource stability.

These findings underscore the need for adaptive water management strategies capable of addressing both drought and flood extremes.

4.3 Recommendations

Based on the findings, the following recommendations are proposed:

1. **Sustained Satellite Monitoring:**

Regular application of NDWI and MNDWI should be institutionalized for annual or seasonal monitoring of surface water dynamics. Continuous observation will improve early detection of hydrological shifts.

2. **Integration with Climate Data:**

Future research should incorporate rainfall, temperature, evapotranspiration, and river discharge data to strengthen understanding of the climate–water relationship.

3. **Flood and Drought Preparedness:**

Areas prone to flooding should be mapped and monitored, particularly following high-index years such as 2025. Similarly, drought-prone patterns resembling 2015 should inform proactive water storage and conservation strategies.

4. **Sustainable Water Resource Management:**

Irrigation efficiency should be improved, and water abstraction regulated to reduce pressure during low-water periods.

5. **Climate-Responsive Urban Planning:**

Urban expansion should incorporate proper drainage infrastructure and avoid encroachment into wetlands and natural water channels to minimize flood risk.

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