

## SPATIOTEMPORAL DYNAMICS OF SURFACE WATER EXTENT IN THE KANO RIVER BASIN, NIGERIA: AN ANALYSIS USING LANDSAT AND SENTINEL-2 MULTI-SPECTRAL IMAGERY (2000–2025)

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**Abstract.** The dynamics of surface water of semi-arid areas require monitoring to measure the resilience of hydrology to climatic fluctuations and human influence. The paper combines twenty-five years of multisensor remotely sensed data to study the spatiotemporal variations in surface water in the Kano River Basin (KRB), Nigeria, one of the largest irrigation-centred agricultural systems in West Africa. Google Earth Engine (GEE) was used to perform the Landsat (5, 7, 8, and 9) and Sentinel-2 imagery by using Cloud Shadow Screening (CSS) and the water extents (annually and seasonally) extracted using the Modified Normalised Difference Water Index (MNDWI) from 2000 through 2025. The dual hydrological regime in the occurrence of water, transition of gains and losses and trend shows a stable, permanent water, which is maintained by the input of groundwater and reservoirs and dynamic seasonal waters that are maintained by the input of monsoon rain. The findings contribute to managing irrigation, preparing for drought and sustainable administration of water as per the Sustainable Development Goals.

**Keywords:** surface water dynamics, MNDWI, remote sensing, semi-arid basin, Kano River Basin, water resources management.

### 1. Introduction

The use of remote sensing to monitor environmental components has been a traditional technology since the launch of the first civilian satellites in the 1970s. Currently, it is intensively used in agriculture and forestry (Raeva & Pavelka, 2020). Processing has changed significantly, with elements of artificial intelligence based on neural networks now being used in many cases (Pešek et al., 2024). It appears that water management will become very important with the growth of the human population and climate change. Surface water resources are essential in the sustenance of ecologies, agricultural production of food, and socio-economic development, especially in semi-arid and developing nations where agricultural productivity, as well as humans and livelihoods are highly dependent on water supply. The variability of surface water in space and time is therefore vital to water resource management in the face of escalating water climatic variability and rising human demands (Gbetkom et al., 2023; Lemoalle et al., 2012). Recent assessments encompassing the globe have shown that the extent of surface water is extremely dynamic and vulnerable to climatic changes, transformations in land-use,

infrastructural development, and resource extraction of groundwater (Pekel et al., 2016; Donchyts et al., 2016). These pressures are likely to grow in Africa as irrigated agriculture grows fast, exerting more and more pressure on scarce freshwater resources (Xie et al., 2022).

In this framework, KRB Cloud Shadow Screening (CSS) that is situated in the northern part of Nigeria in the semi-arid Sudan-Sahelian ecological zone is one of the most important agricultural and hydrological systems in West Africa. The limb sustains massive irrigation programmes managed by huge reservoirs and the most notable are the Tiga and Challawa Gorge dams contributing to the agricultural production on a large scale as another activity under the Kano River Irrigation Project (Nura et al., 2024). Nevertheless, the growing use of surface water, the accelerated growth of population, the uneven distribution of rainfalls, as well as the extensive conversion of land-use, have added pressure to the competition of water resources. The effects of these pressures have changed hydrologics and impacted downstream wetlands and ecosystems (Li et al., 2022), and the evidence-based water management requires the continuous and spatially explicit monitoring of surface water dynamics.

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The development of satellite remote sensing has enabled the ability to observe surface water dynamics at extended periods of time and broad areas at a large scale. The longest history of environmental change is gained through Landsat imagery, which has an archive of continuous 30 m resolutions as far back as 1970s (Wulder et al., 2019). Recently Sentinel-2 images have introduced the ability to observe more by increasing the temporal resolution and spectral resolution, which allows relatively smaller and seasonal water features to be detected (Giulia et al., 2021). Seeking a difference between water and non-water surfaces, spectral indices like the Normalised Difference Water Index (NDWI) (McFeeters, 1996) and the MNDWI (Xu, 2006) can be used, and cloud-computing services like Google Earth Engine can be used to process large archives of satellites using the spectral index and analyse trends across decades on a basin scale (Gorelick et al., 2017). Although the Kano River Basin has strategic hydrological and economic value, sporadic observations have been made regarding the utilisation of surface water dynamics in the basin by applying both Landsat and Sentinel-2 satellite data to find out the effect of spatial and temporal scales. The past research has put most emphasis on the irrigation performance and hydrological modelling and very little on the spatial and temporal changes in the surface waters of a basin-wide (Nura et al., 2022). To fill this gap, the current investigation will integrate Landsat (2000–2025) and Sentinel-2 images to generate high-resolution surface water maps, study long-term variation and change threshold and examine the impact of climatic variability, land-use shift and irrigation control (Drusch et al., 2012). The resulting framework offers an example that can be duplicated to track the surface water in semi-arid basins that face rising environmental pressure (Sent et al., 2021).

## 2. Methodology

### 2.1. Study area

The Kano River Basin (KRB) is located between latitudes 11° 20' N and 12° 30' N and longitudes 8° 20' E and 9° 15' E in the north-Central region of Kano State, Nigeria

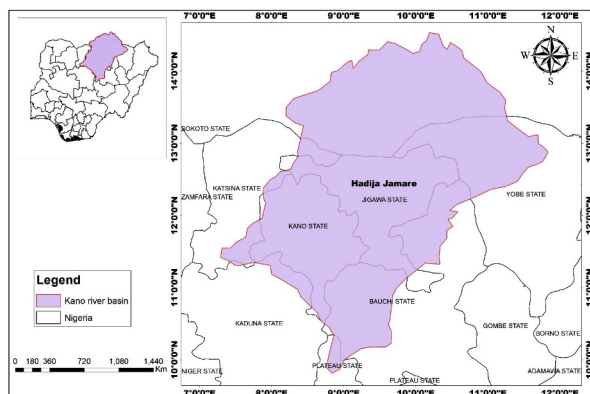


Figure 1. Study area map

(Figure 1). It is a significant sub-catchment of a larger Hadejia-Jama'are-Komadugu-Yobe River system, which eventually flows into Lake Chad in the north-eastern region of the country (The SMEC Group, 2019). The basin is estimated to occupy an area of approximately 12,000km<sup>2</sup> which includes large areas of floodplains, irrigation systems, and large reservoirs like Tiga and Challawa. Its hydrology is mainly controlled by seasonal precipitation experienced in the period of May to September, after which there follows a long dry season, which is dominated by evapotranspiration and irrigation withdrawals.

The Kano River is one of the most important water bodies that is used domestically, for agriculture, and for industry in the highly populated Kano metropolis and the surrounding rural population (Shanono et al., 2024). The landscape of the basin is that of well-rounded plains whose elevations are 400 m to 600 m above sea level, and the basement complex rocks are covered by alluvial deposits in the lowlands. Its climate is semi-arid, and its annual precipitation ranges between 600 mm and 900 mm, with mean temperatures usually over 30°C in the dry season.

### 2.2. Data collection and pre-processing

The study used an integrated remote sensing and geospatial analysis system in GEE to extract, quantify, and analyse the spatiotemporal dynamics of surface water in the Kano River Basin from 2000 to 2025. The technique was a combination of the multi-sensor satellite data of Landsat 5, 7, 8, and 9, and Sentinel-2 to achieve a consistent, cloud-free, and temporally continuous basin coverage throughout the 25-year study period (Table 1).

Table 1. Data used

Satellite / sensor	Platform ID (GEE Collection)	Temporal coverage used	Spatial resolution (m)	Spectral bands used
Landsat 5 TM	LANDSAT/LT05/C02/T1_L2	2000–2011	30	Green (SR_B2), NIR (SR_B4), SWIR1 (SR_B5)
Landsat 7 ETM+	LANDSAT/LE07/C02/T1_L2	2000–2025	30	Green (SR_B2), NIR (SR_B4), SWIR1 (SR_B5)
Landsat 8 OLI	LANDSAT/LC08/C02/T1_L2	2013–2025	30	Green (SR_B3), NIR (SR_B5), SWIR1 (SR_B6)
Landsat 9 OLI-2	LANDSAT/LC09/C02/T1_L2	2021–2025	30	Green (SR_B3), NIR (SR_B5), SWIR1 (SR_B6)
Sentinel-2 MSI (Harmonized)	COPERNICUS/S2_SR_HARMONIZED	2015–2025	10	Green (B3), NIR (B8), SWIR1 (B11)

Surface reflectance products of the Landsat and Sentinel-2 archives were accessed with the help of the GEE data catalog. Specifically, continuity of time was preserved with the help of Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 and 9 Operational Land Imager (OLI), and Sentinel-2 Multispectral Instrument (MSI) images. All pictures were classified by the date (2000–2025) and the distance to the KRB border (object of interest). Each collection was sensor-specifically preprocessed in order to have spectral consistency. A calculation of the surface reflectance on the Landsat data based on the coefficients that were obtained by the USGS (Reflectance = DN x 0.0000275 0.2) and the images obtained by Sentinel-2 were normalized by the numbers 10, 000.

The atmospheric and cloud contamination was minimized by ignoring Sentinel-2 scenes that had a cloud cover of more than 40 percent. The sensors have been selected with band subsets (green, Near-Infrared (NIR), and Short-Wave Infrared (SWIR1) and renamed to facilitate coherence between the combined image set. The harmonized data were then merged to produce a single multi-sensor Image Collection between 2000 and 2025, to have a continuous flow of time.

### 2.3. Derivation of water indices

MNDWI was computed for each image to enhance open water features while suppressing vegetation and built-up land reflectance. The MNDWI was calculated using the equation:

$$MNDWI = \frac{G - SWIR1}{G + SWIR1}, \quad (1)$$

where,  $G$  is the surface reflectance in the green band and  $SWIR1$  is the reflectance in the short-wave infrared band. Pixels with  $MNDWI$  values greater than 0.0 were classified as water, following the thresholding approach commonly applied in surface water studies. This binary classification (1 = water, 0 = non-water) produced annual and seasonal water masks across the study period.

### 2.4. Generation of annual and seasonal water composites

The median of MNDWI was composed using all possible images for each calendar year to obtain an approximation of the inter-annual variation and the gaps between the clouds. This eliminates the sound produced by the temporary weirdities of the edges of the clouds or the fog in the atmosphere. The MNDWI threshold was used to generate a binary water mask per year and producing a stack of 26 band images and denoting the amount of water in a year between 2000 and 2025.

Annual and seasonal composite data were calculated so as to capture the dynamics of intra-annual and inter-annual. The annual surface water covered was identified in terms of composites, and seasonal masks were used

to determine regular (wet-season) and occasional (dry-season) inundation.

### 2.5. Spatiotemporal water dynamics and trend analysis

The long-term water frequency map was calculated by summing all the masks of the yearly water and dividing the sum by the number of years, thus stating the frequency of water presence (01) per pixel. The pixels with the number of occurrences greater than or equal to 0.75 were considered permanent, whereas 0 to 0.75 were seasonal.

A pixel-wise linear regression was estimated to determine long-term hydrological patterns to estimate the relationship between water presence (dependent variable  $y$ ) and time (independent variable  $x$ , meaning year). The slope of the regression line ( $\beta_1$ ) quantified the direction and magnitude of change, as expressed by:

$$y = \beta_0 + \beta_1 x + \varepsilon. \quad (2)$$

A positive slope indicated an expansion of surface water extent, while a negative slope denoted contraction or drying trends over the study period.

### 2.6. Detection of water gain and loss

The binary water masks of the baseline year (2000) and the terminal year (2025) were used to compare and determine the water gain and loss. A pixel was classified as water gain when the value changed to 1 (water) when it was 0 (non-water), and water loss when it changed to 0 (non-water). The code was improved further to calculate the yearly gain and loss between the consecutive years (e.g., 2000, 2001, 2002, etc., 2024, 2025) in order to capture progressive change. This enabled the short-term changes in the surface water dynamics to be quantified and not just the net change between the endpoints.

### 2.7. Area computation and statistical analysis

To obtain the surface water area of each annual water mask and derived class (permanent, seasonal, occurrence, gain, loss, and trend), the classified binary raster was multiplied by the pixel area, and all water pixels in the basin boundary were added together. The area (in square kilometers) was summed up by this equation:

$$A = \sum (W_i \times P_i), \quad (3)$$

where,  $W_i$  is the water pixel value (1 for water, 0 for non-water) and  $P_i$  is the pixel area in  $\text{km}^2$  ( $30 \text{ m} \times 30 \text{ m} = 0.0009 \text{ km}^2$ ). These values were aggregated annually to form time series datasets and exported as CSV tables for statistical analysis. The regression slopes and occurrence ratios were used to interpret hydrological stability and transition zones.

## 2.8. Output products

Spatial products (annual water extent, water occurrence frequency, permanent water maps, seasonal water maps, linear trend (slope) maps, and water gain/loss layers) were then all exported as GeoTIFFs. The corresponding tabular summaries that included yearly statistics of areas were exported in the form of a CSV file to continue with quantitative analysis and visualization.

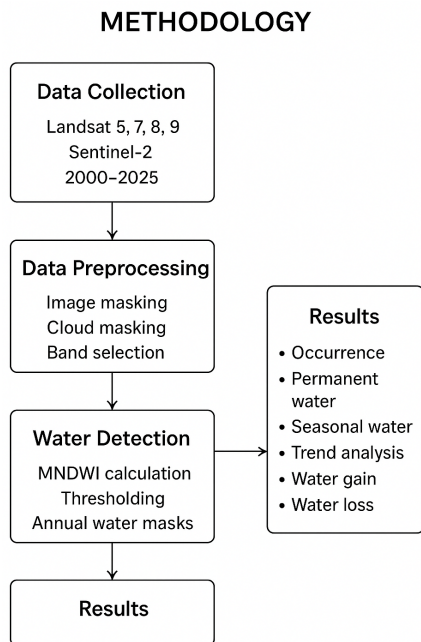


Figure 2. Flowchart methodology

The combination of multi-sensor datasets and large-scale calculations, and cloud computing offered by GEE made the Kano River Basin surface water development efficient, systematic, and at high resolution, over a quarter-century.

The research flowchart methodology is shown in Figure 2.

## 3. Results

The research findings to be discussed here pertain to the changes in surface water in the study area from 2000 to 2025. The results demonstrate the changes in water extent, occurrence frequency, and trends over space and time derived from Landsat and Sentinel-2 images through MNDWI. Besides, the graphs and statistics reveal the transformations of permanent, seasonal, gained, and lost water bodies over the past 25 years.

Surface water dynamics of the KRB between 2000 and 2025 show that it has a complicated hydrological system, which is likewise unequally stable in water classes (Table 2). The statistics indicate that long-term water bodies are highly resilient in the face of interannual climate variations, and they have a relatively stable surface area with a limited degree of variation. This is an even

Table 2. Surface water trends 2000–2025

Year	Water occurrence 2000-2025(area_km <sup>2</sup> )	Seasonal water flow 2000-2025(area_km <sup>2</sup> )	Permanent water flow 2000-2025(area_km <sup>2</sup> )
2000	370.262	100.367	269.895
2001	426.285	154.077	272.208
2002	383.768	113.859	269.909
2003	359.879	90.777	269.101
2004	348.945	84.892	264.053
2005	321.144	76.667	244.476
2006	331.573	83.748	247.825
2007	361.122	90.755	270.367
2008	343.192	73.276	269.915
2009	293.670	54.886	238.784
2010	310.691	56.270	254.421
2011	323.013	63.151	259.861
2012	480.477	207.263	273.214
2013	409.473	137.185	272.288
2014	344.015	79.457	264.558
2015	351.395	80.481	270.913
2016	353.078	80.667	272.411
2017	320.413	49.798	270.615
2018	333.062	64.073	268.989
2019	357.265	86.140	271.125
2020	387.666	113.846	273.820
2021	392.889	119.361	273.528
2022	390.321	118.368	271.952
2023	382.533	114.330	268.203
2024	369.733	105.371	264.362
2025	358.452	95.361	263.016

pattern of stability, indicating that these water bodies are established mainly by groundwater outflow and interactions with aquifers instead of direct precipitation, which has been well documented in arid landscapes where the systems that are groundwater-based are hydrologically stable despite changes in climate (Leblanc et al., 2022).

By comparison, seasonal waters are highly sensitive to climatic conditions, with changes in surface area attaining over 150 km<sup>2</sup> between extreme years. The high correlation between total water presence and seasonal water area reveals that the interannual variability of the total water presence is mainly governed by the broadening and narrowing of seasonal waters. This tendency can be compared with the findings of El-Rawy et al. (2023), who reported the same hydrological behaviour in semi-arid basins where ephemeral water resources act as the main buffer to the variation of rainfalls.

The outstanding year 2012 is one of the hydrological extremes where the water extent of the seasons was

207.3 km<sup>2</sup>, which is in line with climate extremes seen in the Upper Niger basins over the years (Ayeni et al., 2024). The following decrease in the permanent water area between the years 2017–2025 implies the possibility of the systemic shifts in the interactions between groundwater and surface water, which could be the result of the accumulated effects of the decreased recharge and the rising pressure on the extractions, as observed in the recent evaluation of the water security of the region (The SMEC Group, 2019).

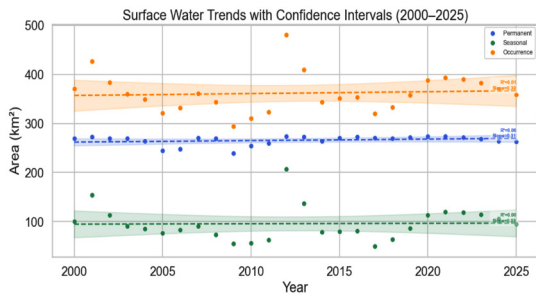


Figure 3. Permanent water flow, seasonal water flow, and water occurrence graph

These results bring out the importance of integrating water resource management policies that acknowledge the complementary roles of permanent and seasonal waters in such a way that groundwater systems are not compromised, but rather careful ways of accessing the benefits of seasonal resources offered by variable seasonal waters are adopted.

Figure 3 shows the hydrological dynamics of the Kano River Basin through different graphs that reveal a significantly greater spatial extent and stability of permanent water bodies compared to highly variable seasonal water resources. The huge difference in the areas of permanent and seasonal water classes emphasizes the role of groundwater-fed systems as the main source of year-round water availability, while seasonal waters mirror the region’s strong dependency on rainfall. These results corroborate the findings of Leblanc et al. (2022), who underline the significance of aquifer contributions to the surface water permanence in semi-arid African basins.

The narrow confidence intervals around permanent water trends show that these are stable hydrological systems, while the wider intervals for seasonal waters indicate their vulnerability to climate variability, which is in line with the study of El-Rawy et al. (2023) that revealed climate-driven surface water fluctuations in semi-arid regions. This difference in stability between the two has major implications for water resource management, implying that efforts aimed at conservation should first focus on safeguarding groundwater recharge areas so as to be able to supply permanent water sources, at the same time developing the necessary adaptive strategies for the management of highly variable seasonal resources.

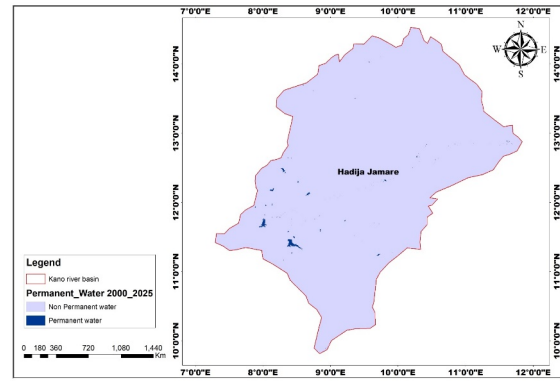


Figure 4. Seasonal water map 200–2025 of the Kano River Basin

Seasonal changes in surface water in the Kano River Basin in the temperate zone of Nigeria from 2000 to 2025 are shown in Figure 4 in a very clear way and reveal the crucial hydrological changes of the semi-arid region. The spatial distribution marks extreme water body extent changes with permanent water channels following relatively stable patterns, while the nearest seasonal water bodies show great interannual variability (Ayeni et al., 2024). This regime mirrors the area’s reliance on seasonal precipitation, whereby ephemeral streams and temporary water bodies become the major agricultural and domestic uses during peak dry seasons. Households are especially dependent on transient water sources for supplemental irrigation and livestock watering, thus their spatial and temporal distribution is a prerequisite for regional water security (Shehu et al., 2023).

The fluctuating water scenes found are consistent with the changing climate and patterns that influence the northern basins of Nigeria, with the rising evaporation rates and irregular precipitation that have deepened the seasonal nature of surface water availability in the area (Tukur, 2018). These changes emphasize the necessity for the adoption of flexible water management schemes that incorporate spatial and temporal variations in water distribution. The map’s recording of these trends over a quarter of a century opens up the way for the formulation of precise water-saving and water-storage strategies to fuel the agricultural economy of the basin and the population growth (Ayeni et al., 2024; Shehu et al., 2023).

The dark blue areas are permanent water bodies, and the lighter area is non-permanent water, indicating that much of the water of the basin is temporary. This spatial distribution corresponds to the hydrology of northern Nigeria, where the surface water system is extremely sensitive to both the rainfall variability and the vast water abstraction by agricultural activities. According to Umar et al. (2019), natural flow regimes in the Kano River Irrigation Project are affected by the irrigation withdrawals and dam operations, which reduce the persistence of water in the floodplains and wetlands of the Hadejia-Jama’are basin. In addition, Pekel et al. (2016) based on multi-decadal Landsat surface water records revealed

that anthropogenic activities, in particular irrigation, damming up of reservoirs, and agricultural growth, are also causing permanent surface water to diminish across the world. The recent climate research also emphasizes that the changes in the annual variability of the West African Monsoon can impact the availability of water in northern Nigeria and can result in severe changes in the runoff of the wet season and the dry season surface water retention (Okafor et al., 2024). These results, in combination, confirm the mapped outcome, demonstrating that the Kano River Basin is turning out to have an ever-changing surface water situation, which is caused by both anthropogenic stressors and climatic variability.

Table 3. Gain and loss, water occurrence, and water trend slope

Year	gain_area_km <sup>2</sup>	loss_area_km <sup>2</sup>	Water occurrence Sq km	Water trend slope area_ km <sup>2</sup>
2000	0	0	370.262	286.474
2001	96.056	40.033	426.285	286.474
2002	48.906	91.423	383.768	286.474
2003	34.167	58.057	359.879	286.474
2004	38.156	49.090	348.945	286.474
2005	32.127	59.927	321.144	286.474
2006	56.440	46.011	331.573	286.474
2007	85.475	55.926	361.122	286.474
2008	29.871	47.801	343.192	286.474
2009	20.919	70.441	293.670	286.474
2010	48.186	31.165	310.691	286.474
2011	39.720	27.399	323.013	286.474
2012	177.803	20.339	480.477	286.474
2013	63.240	134.244	409.473	286.474
2014	13.462	78.920	344.015	286.474
2015	35.501	28.121	351.395	286.474
2016	26.271	24.588	353.078	286.474
2017	9.894	42.559	320.413	286.474
2018	28.935	16.286	333.062	286.474
2019	39.428	15.225	357.265	286.474
2020	47.357	16.956	387.666	286.474
2021	34.448	29.226	392.889	286.474
2022	30.281	32.849	390.321	286.474
2023	36.556	44.344	382.533	286.474
2024	26.965	39.765	369.733	286.474
2025	35.029	46.385	358.452	286.474

The study of hydrological changes of the Kano River Basin shows that water on the surface is complex, with a significant interannual variation in water gains and losses (Table 3). The data show that the basin underwent major dynamics in the water surface extent, and specifically, the

hydrological activities were high in the 2012 extreme wet year, where water gains were 177.803 km<sup>2</sup> compared to only 20.339 km<sup>2</sup> water losses. This outstanding net gain of 157.464 km<sup>2</sup> is a significant hydrologic perturbation, which corresponds to observations of climate extremes recorded in West African river systems by Ndehedehe et al. (2016), who found such extreme events to be a critical source of aquifer recharge and ecosystem stability in semi-arid settings.

The analysis of water gains and losses shows that there are specific hydrological regimes over the study time. The years with equal gains and losses (e.g., 2007, 2020–2022) indicate stable hydrological conditions with sustainable water turnover, whereas the years with disproportionate losses (e.g., 2009, 2013–2014) indicate the period of hydrological stress. This tendency aligns with the results reported by Adetayo (2021) on the effect of rainfall variability on surface water maintenance in Nigerian river basins, where the consecutive years of negative water balance may have a profound effect on the water security and agricultural performance.

The consistent difference between the real water surface and the trend slope area of the long term in the whole study area (286.474 km<sup>2</sup>) indicates a significant change in the hydrological base of the basin. This deviation shows that the modern surface water boundaries are always less than the reference conditions of the past, which is associated with the possibility of long-term changes in the water preservation capacity of the basin. These trends are consistent with the findings of Leblanc et al. (2022) in the Lake Chad Basin, where the systematic changes in the surface water availability have been triggered by combined influences of climate change and anthropogenic pressures.

The period of transition between 2017–2025 is marked by a tendency to increase the balance of gains and losses, which means that the hydrological system may stabilize or adapt to new hydrological norms. Nevertheless, the fact that the basin has experienced a net negative water balance over the years creates an issue regarding the water sustainability in the long term, especially considering that climate forecasts have shown that the region will experience more rainfall variability (Sylla et al., 2016).

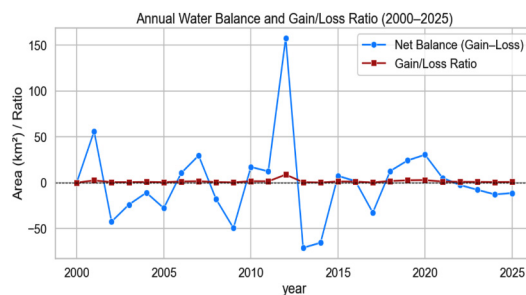


Figure 5. Annual water balance and Gain and loss ratio

Figure 5 is the complex analysis of the Kano River Basin dynamics of the annual water balance between 2000 and 2025 and indicates important trends in the dynamics of hydrological stability and variability of resources. The time series development of both the net water balance (gain-loss) and the ratio of the gain/loss illustrates how the basin has passed through various hydrological regimes that experience water surplus and water deficit. Another anomaly observed in the hydrological year 2012 was that the year had a high positive net balance and a gain/loss ratio of 8.0, which shows a huge amount of inflow of water compared to losses. This extreme event is consistent with other reports, such as those by Ndehedehe et al. (2016), who have reported the same episodic flooding events in West African river basins as important processes in recharging the aquifer and restoring the ecosystem, even though it may have short-term disruptive effects.

It also indicates that, after 2012, the ratio of gain/loss became much more balanced, which may indicate a possible stabilization of the hydrological system or the adjustment to new climatic standards. Nonetheless, negative net balance years have been fairly common in 2002–2005 and 2013–2014, suggesting that the occurrence of negative net balance years reflects points of extreme hydrological stress, which have been documented in the area of northern Nigeria (Sylla et al., 2016). The consequences of these periods of deficit on water security, agricultural output, and ecosystem health are significant, which underscores how vulnerable the basin is to the changes in climate.

The shift to the more moderate gain/loss ratio in the recent years (2018–2025) could imply the development of a new balance in the hydrological processes in the basin, which could also have the influence of both the natural system change and human intervention in the water management. This trend is similar to what Adetayo (2021) observed, as they found that a few river basins in Nigeria have been becoming more resilient to erosion and deposition as a result of better water conservation measures and adaptation techniques. Nevertheless, the long-standing discrepancy highlights the constant problem of controlling the water resources in a highly dynamic hydro-climatic environment.

The correlation between the net balance and the gain/loss ratio gives considerable information on the water resource management as years with negative net balance and a balanced ratio (e.g., 2014, 2023–2025) are evidence of water depletion in gradual terms whereas years with negative net balance and ratio (e.g., 2012, 2015–2016) correspond to water stress in acute terms. This distinction is essential in coming up with specific adaptation plans because such different regimes of stress need particular management plans, whether it is responding to emergencies in the short term or planning on sustainable use of water over the long term.

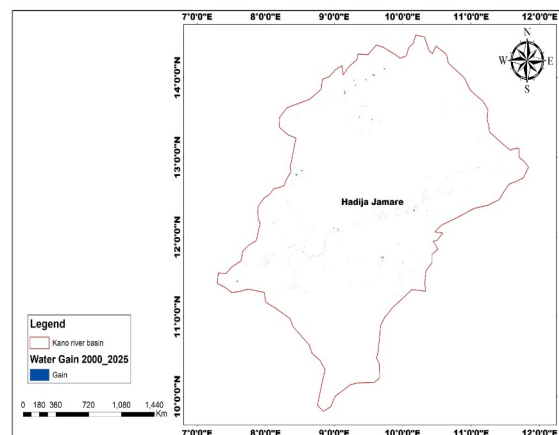


Figure 6. Water gain 2000–2025

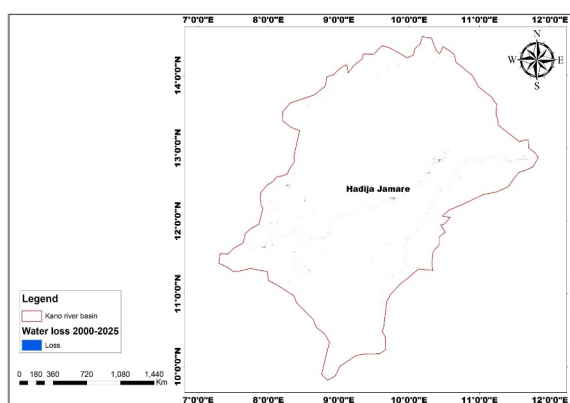


Figure 7. Water loss 2000–2025

Figures 6–7 critically analyze the spatial changes of hydrology in the Kano River Basin and show particular geographical patterns in water gaining and loss processes from 2000 to 2025. The understanding of the space distribution of water gains indicates that there are concentrated accumulation areas, mainly along the main river channels and the topographic depressions, and this indicates that water is likely to find its way into the aquifer through preferential pathways. It is consistent with the results of Ndehedehe et al. (2016), who described similar focused recharging processes in semi-arid West African basins in which the accumulation of water is governed by the geological structures and the soil properties.

On the other hand, the water loss map shows that there are large regions with surface water loss, especially in the extreme parts of the basin and regions that have shallow aquifers. The spatial complementarity of patterns of gain and loss shows a restructuring of water resources in the basin, where the more vulnerable areas are subject to loss, which is seen to be storage-limited. Such spatial distinction is aligned with findings by Leblanc et al. (2022) in the Lake Chad Basin, where the hydrological shifts have been prompted by climate variability and anthropogenic stresses.

The high-water gains in particular areas indicate the significance of such areas in the preservation of water

security in the basin and should therefore be given priority in conservation at the expense of aquifer recharge programs. In the meantime, the ubiquitous nature of water losses highlights the susceptibility of significant areas of the basin to hydrological alteration, which requires specific adaptation strategies to afflicted communities and ecosystems. Such patterns may be used to offer useful information on how to create localized interventions in water management in the basin to consider the heterogeneous nature of hydrological changes.

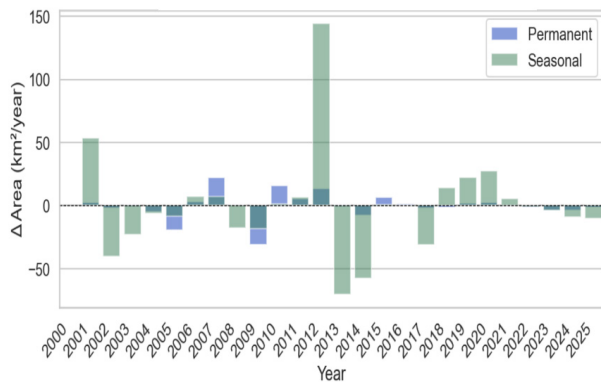


Figure 8. Annual rate of water surface change (2000–2025)

According to Figure 8, the hydrological actions of permanent and seasonal water bodies in the Kano River Basin between the years 2000 and 2025 are radically different. The statistics show that seasonal waters are highly variable, showing yearly variations of more than 100 km<sup>2</sup>/year at the extreme years, whereas permanent waters are incredibly stable with very low variation at an annual rate. This response difference reminds us of the unique hydrological processes that govern these water classes, where seasonal waters act as the dynamic subsystem that is sensitive to the variability of precipitation, and permanent water is the stable system that is buffered by interaction with the groundwater.

The abnormally positive seasonal water change rate value in 2012 is consistent with recorded climate extremes in northwestern Nigeria, where there are rare episodes of precipitation that might lead to massive yet short-term increases in surface water (Ndehedehe et al., 2016). On the other hand, the pattern of nearly zero change rates of permanent waters across the study period indicates a reliable groundwater contribution that, even with climate variability, ensures hydrological stability and is also found in other similar semi-arid basins by Leblanc et al. (2022).

The negative change rates in seasonal waters are more often observed in the post-2010 period, showing a pattern of reduced contraction phases. This trend coincides with the climate forecasts of the area where more variability of the rainfall and higher rates of evaporation are expected (Sylla et al., 2016). The consistent stability of these permanent waters during such changes is an indicator of their extreme significance as drought refugia and

an indicator of the significance of safeguarding groundwater systems, which support them.

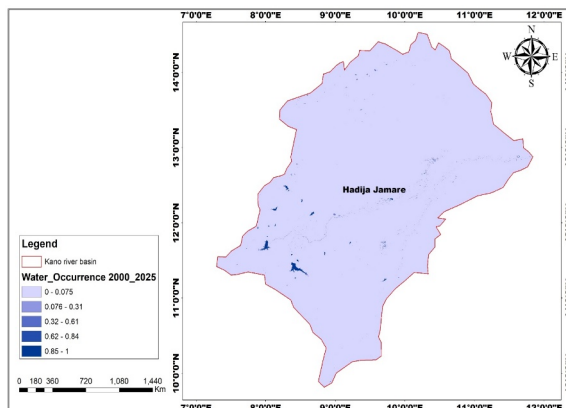


Figure 9. Water occurrence map of the Kano River Basin 2000–2025

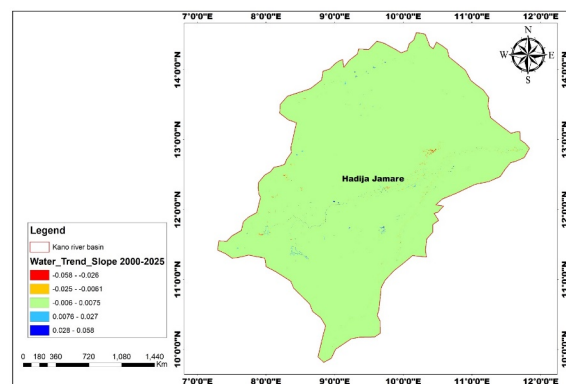


Figure 10. Water trend slope map of the Kano River Basin 2000–2025

In Figures 9–10, the distribution of where water occurs in the Kano River Basin in the period between 2000 and 2025 is displayed. The regions that are depicted in darker blue are the areas where the surface water always existed throughout 25 years, and light colors indicate the areas where the water has always appeared randomly. The preponderance of light colors in the basin will indicate that the majority of the surface water is seasonal, and influenced chiefly by the distribution and cycles of precipitation; the more permanent masses of water, indicated by the dark blue zones, are limited to the reservoirs and fixed sections of rivers.

This trend aligns with the previous results that the surface water systems of the North of Nigeria are very affected by climatic seasonality and hydrological changes relating to the West African Monsoon (Okafor et al., 2024). Human actions also increase such fluctuations: the natural flow regime is disturbed by such areas as reservoir operations, water diversion, and irrigation schemes within the Kano River Irrigation Project, and makes wetlands less permanent throughout the year (Umar et al., 2019). Satellite-based measurements in the entire world indicate the same patterns where agricultural

water extraction and infrastructural creation result in a decline in permanent water bodies and an escalation of intermittent appearance of water (Pekel et al., 2016). In such a way, the space distribution in Figure 10 indicates a basin which becomes more and more hydrologically heterogeneous, being influenced by the climatic control in addition to anthropogenic water demand.

Figure 11 shows that there is a lot of spatial heterogeneity in water surface trends in the Kano River Basin between 2000 and 2025. The spatial pattern exhibits definite groups of both increasing and decreasing patterns, with certain sub-basins having significant concentrations of positive patterns (0.028–0.058) and other regions displaying moderate declines (0.058–0.026). This localized space patterning indicates that hydrological processes are locally restricted, which may be caused by geology, land use plans, and human interventions.

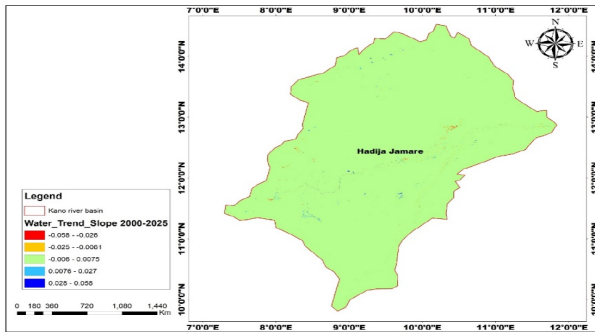


Figure 11. Principal component analysis of water components

The clustering of the positive trends can suggest the regions of increased water retention or concentrated recharge, which may either represent a positive hydrogeological environment or the effective practice of water conservation. On the other hand, regions with negative trends are probably the regions of rising water stress because of both climate and anthropogenic stressors, as found in other similar semi-arid regions by Leblanc et al. (2022). Such spatial distinction offers a useful clue on specific areas that have to be prioritized in conserving water resources, and those that can be replicated to ensure the same effective water conservation methods.

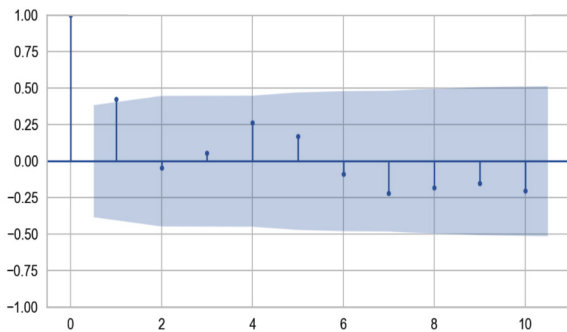


Figure 12. Autocorrelation of permanent water extent 2000–2025

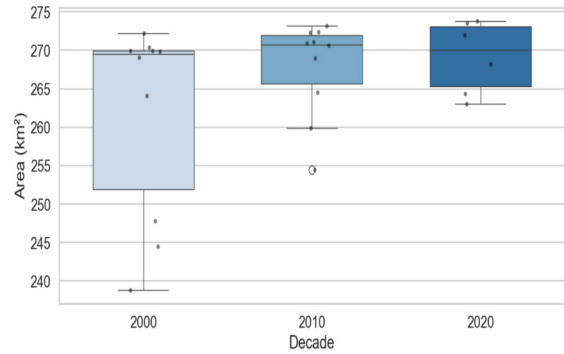


Figure 13. Decadal variation of permanent water area using box plot 2000–2025

This pattern indicates substantial year-to-year memory in the hydrological system, where water conditions in one year strongly influence subsequent years. Such persistence aligns with findings by Ndehedehe et al. (2016) regarding the inertial characteristics of groundwater-dependent systems in semi-arid Africa, where aquifer storage creates hydrological memory that buffers against interannual climate variability.

Figure 12 reveals notable decadal-scale variations in permanent water area, with the 2010–2020 period showing distinct characteristics from preceding and subsequent decades. This decadal patterning suggests the influence of low-frequency climate oscillations on basin hydrology, consistent with observations by Sylla et al. (2016) of decadal hydrological cycles in West African river systems linked to Atlantic Ocean temperature anomalies.

Figure 13 demonstrates that the first two principal components explain 81% of the variance in water components, indicating strong coordinated behavior among different hydrological elements. The high explanatory power of PC1 (58.8%) suggests dominant common drivers affecting all water components, while PC2 (22.2%) likely represents secondary factors creating differential responses. This dimensionality reduction aligns with multivariate analyses by Leblanc et al. (2022), who identified similar integrated hydrological responses to climate forcing in the Lake Chad Basin.

Table 4. Summary statistics

Metric	Mean Area (km <sup>2</sup> )	Std. Dev.	MK p-value	Sen Slope
Permanent	265.7619	9.394664	0.290058	0.091438
Seasonal	95.93951	34.14229	0.860033	0.183989
Occurrence	361.7043	39.45777	0.56659	0.533497

Table 4 provides a detailed statistical description of the hydrological elements of the KRB, which is characteristic of radically different stability regimes. It is a high degree of stability of permanent water with a very small variation (coefficient of variation = 3.5%) and a high

volatility of seasonal waters (coefficient of variation = 35.6%), as these water sources are different in terms of source dependence on groundwater and precipitation. The Mann-Kendall  $p$ -values of all classes of water are not significant ( $p > 0.05$ ), which shows that there were no statistically significant monotonic trends over the study period in spite of the positive Sen slope estimates. This implies that to find directional changes, although not statistically significant at traditional criteria, a trend seen already by Ndehedehe et al. (2016) in other West African basins, where high interannual variability tends to obscure trends.

Such marked disparity in the standard deviation of permanent (9.39 km<sup>2</sup>) and seasonal (34.14 km<sup>2</sup>) waters reflects the difference in hydrological response between seasonal and permanent waters, in which the seasonal waters are extremely sensitive to changes in climate, whereas the permanent waters are relatively stable through the buffering of groundwater. The gradient of the positive Sen (slope of water occurrence of 0.53 km<sup>2</sup>/year) shows that it is a gradually increasing trend, but statistically non-significant, which is consistent with a report by Leblanc et al. (2022) who discovered that in many semi-arid basins, the interannual variability is high, thus making it difficult to identify the trend over decadal time periods.

## 4. Discussion

The multi-decadal analysis of the spatiotemporal distribution of the surface waters in the Kano River Basin (2000–2025) shows that the system is defined by two opposite water regimes, namely stable permanent surface waters and seasonal and irregular water surfaces. As demonstrated in Figure 3 and Table 2, permanent water had a comparatively stable area during the course of studies, and it was changing in a rather limited range (mean  $\approx$  266 km<sup>2</sup>). Seasonal water, on the other hand, showed significant interannual variability with a range of <60km<sup>2</sup> to over 200km<sup>2</sup> during extreme years. This contrast denotes that a groundwater-surface water interaction supports permanent water bodies in the basin, and climatic variability is buffered, which is in line with what has been observed in other semi-arid basins of this type (Leblanc et al., 2022).

### 4.1. Permanent water bodies stability

As shown in Figure 5, permanent water areas were still spatially concentrated around the larger reservoirs (Tiga and Challawa Gorge) and main river channels. Their survival over the 25 years suggests that they are highly hydrologically resilient. The interannual variation shown in Table 2 is limited in permanent water, indicating that reservoirs and groundwater are the sources sustaining such water bodies. This observation is in line with that of Umar et al. (2019), who explained how controlled flows

over the Kano River Irrigation Project keep upstream areas perennial water even during extended dry periods.

The trend results (Table 4) of the Mann-Kendall trend also support the stability of permanent water; that is, the monotonic tendency of it cannot be established statistically. This is in accordance with the hydrological memory effects of Ndehedehe et al. (2016), in which the effect of aquifer contributions maintains perennial water bodies under rainfall variations.

### 4.2. Seasonal water as a climate-based element

There was excessive fluctuation of seasonal water in the basin (Figure 4). Table 2 shows changes in year-to-year of over 150 km<sup>2</sup> that occur in the extreme wet and dry periods, showing that the variability of rainfall and timing of the West African Monsoon is very sensitive. This is a dynamic behaviour that is indicative of rainfall-runoff dependency, and agrees with existing studies in semi-arid West Africa, where seasonal waters serve as a rapid response system to climatic variations (El-Rawy et al., 2023). The peak seasonal water growth was recorded in 2012, with the exceptionally wet year, where the water extent reached over 207km<sup>2</sup> (Table 2). This hydrological anomaly correlates with recorded regional floods and intensification of monsoons in northern Nigeria and the Sahel (Ayeni et al., 2024).

### 4.3. Water gains, losses, and hydrological transitions

The analysis of water gain and loss (Table 3 and Figures 7–8) indicated alternating hydrological periods. Spatially, concentration of water is observed along river floodplains and depressions, indicating a preference in recharge pathways, but extensive losses were experienced at the basin margins. These trends represent hydrological reorganization, as they are in line with the actions of climate extremity and water extraction by Ndehedehe et al. (2016).

The outstanding net water gain in 2012 (+157 km<sup>2</sup>) represents a hydrological pulse in the system, which indicates that episodic wet seasons play a critical role in providing recharge and ecological recovery to the semi-arid basins (Sylla et al., 2016). By contrast, the 2013–2014 year indicates that the main loss of water has occurred, which is in line with a decrease in precipitation and the increase in the evapotranspiration rates.

### 4.4. Long-term trends and occurrence of water

The water occurrence map (Figure 9) revealed that a large portion of the basin was found to be under the dominance of low-frequency water appearance, indicating intense seasonal hydrological behaviour. Only controlled reservoirs and consistent stretches of rivers received permanent water, and the rest of the locations were provided with intermittent flooding. Pekel et al.

(2016) had a worldwide pattern which indicated that extension of irrigation, the control of reservoirs, and climatic changes decrease the permanent water surfaces and promote intermittent water bodies.

The trend slope map (Figure 10) indicated spatial heterogeneity with certain sub-catchments having positive surface water trends (expansion) and others having undergone long-term shrinkage. This spatial mosaic represents localized controls, such as land-use intensification, geology, and irrigation withdrawals.

#### 4.5. Policy relevance and sustainability implications

The implications of this research study on sustainable development are high, and they directly translate to the United Nations Sustainable Development Goals (SDGs). This study can help people make wise decisions on how to allocate freshwater resources by mapping regions where there is permanent and seasonal water, and regions that have water gains and losses. This is especially pertinent to SDG 6 (Clean Water and Sanitation), since the process of identifying stable and depleting water areas will contribute to the improvement of the long-term water-security planning and allow for the management of freshwater resources more sustainably.

The findings are also consistent with SDG 2 (Zero Hunger), as the agriculture of the Kano River Basin is largely dependent on irrigation. The spatial behaviour of seasonal water bodies is vital in helping to optimise the irrigation schedules, enhance the efficiency of water, and plan agricultural activities based on the real availability of water. This information fortifies food-security plans in an area where food production depends on seasonal flooding and controlled discharges out of reservoirs.

Similarly, the research contributes to SDG 13 (Climate Action) by presenting evidence on the rising hydrological variability, which is related to climate variability. Early warning indicators, which can be used in climate adaptation planning and drought preparedness, are the ability to individualize extreme wet years, long dry intervals, and long-term water loss zones. Moreover, mapping of the consistent water positions can also be used in SDG 15 (Life on Land) as it identifies ecologically sensitive wetlands and natural recharge areas that need to be conserved to preserve the biodiversity and hydrological balance.

Comprehensively, spatial knowledge obtained during this study offers important advice to policy makers, basin managers, and irrigation authorities. Knowledge of the location of water as either permanent, seasonal, increasing, or decreasing makes it possible to adjust irrigation demand according to the actual hydrological conditions, prioritize natural recharge areas in order to avoid excessive abstraction, and strategize against extreme hydrological events, including flooding or drought. The remote sensing and cloud-based geospatial analytics integration

provides a sensible and cost-effective hydrological monitoring system in a semi-arid environment where agricultural livelihood relies highly on the presence of water. The adopted methodological framework, which involves the integration of Landsat and Sentinel-2 data in Google Earth Engine, creates a scalable decision-support instrument that will help monitor the situation and make decisions based on data in the Kano River Basin and other similar basins subject to water stress due to climate change.

#### 5. Conclusions

This paper has analysed the dynamics of surface water in the Kano River Basin between 2000 and 2025 based on the multi-sensor satellite measurements (Landsat and Sentinel-2) with the help of Google Earth Engine. The study was able to map permanent and seasonal water bodies, measure annual and seasonal changes, identify water gains and losses, as well as measure long-term hydrological trends by applying the Modified Normalized Difference Water Index (MNDWI) at a basin-wide level.

As the findings reveal, the Kano River Basin has a dual hydrology, i.e., permanent water bodies are relatively stable during the 25 years, and seasonal water bodies demonstrate great variability over the years. The majority of permanent waters are streams of more significant rivers (reservoirs) and groundwater inflows that are maintained by hydraulic infrastructure releases, which render them less sensitive to interannual climate variations. Conversely, seasonal waters are extremely skewed to variation in rainfall and evaporation, which is indicative of the implication of the West African Monsoon and the regional climate processes. The highest levels of interannual variability occurred in 2012, a super hydrologic year with heavy rains and a seasonal water extent greatly expanded, and drier years, like 2013–2014, with a huge loss.

Spatial analysis showed that areas of water gain were mostly in river floodplains and topographic depressions, which are considered preferential routes of recharge, whereas water loss is more widespread in the peripheral areas, which are susceptible to hydrological stress and land-use transformation. These trends indicate a mode of hydrological rearrangement of the basin, whereby water is being condensed in a few more robust areas. It can be further noted by the trend and water occurrence maps that the presence of water is improving in certain regions over time, whilst in other regions it is declining in the long term due to more irrigation being drawn, population pressure, and climatic variability.

The results of the research provide some important points that should be used in the management of water resources on a sustainable basis. The study helps make informed decisions by assisting in the operation of reservoirs, scheduling of irrigation, preparing against floods, preventing droughts, and conserving wetlands by

recognizing the location of water that does not change, diminish, or show intermittence. The findings support the importance of aligning the water demand of agricultural activities with long-term hydrological sustainability, especially in a semi-arid environment, where the surface water resource is getting strained.

## 6. Recommendations

Based on the findings, the policy and research directions to be taken in the future could be determined. This is present as the permanent and seasonal waters are well spaced, and therefore, the water management strategies should be distinguished. Water bodies should be sanctified as key hydrological anchor points, especially for groundwater recharge. Conversely, the seasonal water bodies are to be integrated into the adaptive systems where water is distributed according to the fluctuation of the monsoon strength and the rate of evaporation. The inclusion of satellite-based surveillance in the normal basin management should be incorporated by the policy makers so that the decisions made on water allocation are not hindered by assumptions.

Moreover, the water loss hotspots are outlined, which can suggest that the intensified control of the land-use conversion should be taken into account, particularly when the agricultural lands of the ecologically sensitive floodplains and shallow layers of the aquifer are developed. Data-driven irrigation scheduling, agricultural processes with little water use, and preservation of recharge zones will make water more resilient. Even more research would be done to bring together socio-economic and groundwater data to formulate a coupled surface groundwater hydrological model, which will improve knowledge of the interaction of water, energy, and food processes in the basin.

This satellite remote sensing and cloud-computing technology research project will offer a cost-effective, scalable system of hydrological surveillance, a system reproducible in other semi-arid regions with such problems as this. Effective implementation of the insights would aid in achieving national water security targets and Sustainable Development Goals, in particular, clean water (SDG 6), food security (SDG 2) and climate resilience (SDG 13), and ecosystem conservation (SDG 15). Simply, the findings justify the importance of using scientific evidence in the water governing system in the Kano River Basin in such a way that the river becomes productive, resilient, and sustainable for future generations.

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## References

- Adetayo, A. O. (2021). Assessment of impact of rainfall variability on water supply in Ibadan South West local government area, Oyo State, Nigeria. *Journal of Applied Sciences and Environmental Management*, 25(8), 1385–1388. <https://doi.org/10.4314/jasem.v25i8.15>
- Ayeni, A. O., Sawa, B. A., & Bello, Y. M. (2024). Climate variability and surface water resources in semi-arid Nigeria. *Nigerian Journal of Hydrological Sciences*, 45(2), 112–125.
- Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., & van de Giesen, N. (2016). Earth's surface water change over the past 30 years. *Nature Climate Change*, 6, 810–813. <https://doi.org/10.1038/nclimate3111>
- Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, 120, 25–36. <https://doi.org/10.1016/j.rse.2011.11.026>
- El-Rawy, M., Batelaan, O., Al-Arifi, N., Alotaibi, A., Abdalla, F., & Gabr, M. E. (2023). Climate change impacts on water resources in arid and semi-arid regions: A case study in Saudi Arabia. *Water*, 15(3), Article 606. <https://doi.org/10.3390/w15030606>
- Gbetkom, P. G., Crétaux, J.-F., Tchilibou, M., Carret, A., Delhoume, M., Bergé-Nguyen, M., & Sylvestre, F. (2023). Lake Chad vegetation cover and surface water variations in response to rainfall fluctuations under recent climate conditions (2000–2020). *Science of the Total Environment*, 857(2), Article 159302. <https://doi.org/10.1016/j.scitotenv.2022.159302>
- 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>
- Lemoalle, J., Bader, J.-C., Leblanc, M., & Sedick, A. (2012). Recent changes in Lake Chad: Observations, simulations and management options (1973–2011). *Global and Planetary Change*, 80–81, 247–254. <https://doi.org/10.1016/j.gloplacha.2011.07.004>
- Li, B., Yang, G., Wan, R., Lai, X., & Wagner, P. D. (2022). Impacts of hydrological alteration on ecosystem services changes of a large river-connected lake (Poyang Lake), China. *Journal of Environmental Management*, 310, Article 114750. <https://doi.org/10.1016/j.jenvman.2022.114750>
- McFeeters, S. K. (1996). The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432. <http://doi.org/10.1080/01431169608948714>
- Ndchedehe, C., Awange, J., Agutu, N., Kuhn, M., & Heck, B. (2016). Understanding changes in terrestrial water storage over West Africa between 2002 and 2014. *Advances in Water Resources*, 88, 211–230. <https://doi.org/10.1016/j.advwatres.2015.12.009>
- Okafor, G. C. Ogbu, K. N., Agyekum, J., Limantol, A. M., & Larbi, I. (2024). Rainfall projections under different climate scenarios over the Kaduna River Basin, Nigeria. *Discover Environment*, 2, Article 89. <https://doi.org/10.1007/s44274-024-00127-0>

- Pekel, J.-F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540, 418–422. <https://doi.org/10.1038/nature20584>
- Pešek, O., Brodský, L., Halounová, L., Landa, M., & Bouček, T. (2024). Convolutional neural networks for urban green areas semantic segmentation on Sentinel-2 data, *Remote Sensing Applications: Society and Environment*, 36, Article 101238. <https://doi.org/10.1016/j.rsase.2024.101238>.
- Raeva, P., & Pavelka, K., Jr. (2020) Geospatial and temporal analyses of rural area for vegetation analysis. *Stavební obzor – Civil Engineering Journal*, 29(2). <https://doi.org/10.14311/CEJ.2020.01.0021>
- Sent, G., Biguino, B., Favareto, L., Cruz, J., Sá, C., Dogliotti, A., Palma, C., Brotas, V., & Brito, A. C. (2021). Deriving water quality parameters using Sentinel-2 imagery: A case study in the Sado Estuary, Portugal. *Remote Sensing*, 13(5), Article 1043. <https://doi.org/10.3390/rs13051043>
- Shanono, N., Nasidi, N. M., Abdullahi, A. H., & Umar, S. I. (2024, November 5–8). Dams utilization analysis and potentials to enhance irrigated agriculture in Kano State, Nigeria. In *Proceedings of the 14th Nigeria Association of Hydrological Sciences Conference (Okitipupa 2024)* (pp. 512–518). Olusegun Agagu University of Science and Technology, Okitipupa, Ondo State, Nigeria.
- Shehu, A. M., Garba, M. L., & Ibrahim, A. D. (2023). Indigenous adaptation strategies to water variability in the Kano region. *Journal of Arid Environment Studies*, 28(3), 45–58.
- Sylla, M. B., Nikiema, M., Gibba, P., Kebe, I., & Klutse, N. A. B. (2016). Climate change over West Africa: Recent trends and future projections. In J. Yaro & J. Hesselberg (Eds.), *Adaptation to climate change and variability in rural West Africa* (pp. 25–40). Springer. [https://doi.org/10.1007/978-3-319-31499-0\\_3](https://doi.org/10.1007/978-3-319-31499-0_3)
- The SMEC Group. (2019). *Preparation of strategic action plan for the development of water resources in the Komadugu Yobe Basin – Part 5: Annex 5.1 – Basin Water resources assessment summary*. [https://www.afdb.org/sites/default/files/5\\_kyb\\_sap\\_annex\\_5.1\\_basin\\_water\\_resources\\_assessment\\_summary.pdf](https://www.afdb.org/sites/default/files/5_kyb_sap_annex_5.1_basin_water_resources_assessment_summary.pdf)
- Tukur, A. I., Nabegu, A. B., Umar, D. A., Olofin, E. A., & Sulaiman, W. N. A. (2018). Groundwater condition and management in Kano region, northwestern Nigeria. *Hydrology*, 5(1), Article 16. <https://doi.org/10.3390/hydrology5010016>
- Umar, D. A., Ramli, M. F., Aris, A. Z., Jamil, N. R., & Tukur, A. I. (2019). Surface water resources management along Hadejia River Basin, northwestern Nigeria. *H<sub>2</sub>Open Journal*, 2(1), 184–199. <https://doi.org/10.2166/h2oj.2019.010>
- Wulder, M. A., Loveland, T. R., Roy, D. P., Crawford, C. J., Masek, J. G., Woodcock, C. E., Allen, R. G., Anderson, M. C., Belward, A. S., Cohen, W. B., Dwyer, J., Erb, A., Gao, F., Griffiths, P., Helder, D., Hermosilla, T., Hipple, J. D., Hostert, P., Hughes, M. J., ... & Zhu, H. (2019). Current status of the Landsat program, science, and applications. *Remote Sensing of Environment*, 225, 127–147. <https://doi.org/10.1016/j.rse.2019.02.015>
- Xie, J., You, J., Ma, Z., Deng, X., Lin, P., & Gao, J. (2022). Methodology for including reservoir regulation in water scarcity evaluation. *Journal of Cleaner Production*, 365, Article 132657. <https://doi.org/10.1016/j.jclepro.2022.132657>
- Xu, H. (2006). Modification of the normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14), 3025–3033. <https://doi.org/10.1080/01431160600589179>