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Assessment of Hydro-Morphometric Characteristics and Seasonal Water-Budget Dynamics of Lake Ruma Wetland: Implications for Irrigation and Livestock Production in North-Eastern Nigeria

James Thomas[1], C.Y Oche[2], N.L Binbol[3]

[1,2,3] *Department of Geography and Planning, University of Jos, Plateau State, Nigeria*

ABSTRACT

Wetlands provide important water resources for agricultural production, particularly in seasonally dry environments where rainfall is concentrated within a short period of the year. However, the agricultural usefulness of wetland water depends not only on the quantity stored but also on basin morphology, hydrological connectivity, seasonal replenishment, and the balance between water inputs and losses. This study assessed the hydro-morphometric characteristics and water-budget dynamics of Lake Ruma Wetland in Song Local Government Area, Adamawa State, north-eastern Nigeria, to determine their implications for irrigation and livestock production. Field surveys, GPS-based spatial delineation, bathymetric measurements, digital elevation model analysis, and long-term hydrological data were integrated to characterize the physical dimensions, storage capacity, hydrological connectivity, and seasonal water availability of the wetland. Lake Ruma has an elongated morphology, with a maximum length of 2.18 km, maximum width of 0.59 km, open-water surface area of 1.52 km², maximum depth of 2.23 m, mean depth of 0.97 m, and estimated water volume of approximately 1.47 million m³. The wetland receives water through multiple pathways, including direct rainfall, perennial stream inflow, seasonal river overflow, and catchment runoff. Water-budget analysis revealed pronounced seasonal variability. Positive mean water-balance conditions were restricted to July–September, with surpluses of 102.58, 82.20, and 64.73 mm, respectively, whereas deficits occurred during the remaining months. Annual mean inflow was 289.18 mm compared with a mean outflow of 702.84 mm, producing a mean annual deficit of 413.66 mm. Deficit conditions occurred in 28 of the 30 years analysed, while only two years recorded annual surpluses. The findings demonstrate that Lake Ruma possesses appreciable physical water-storage capacity but limited year-round hydrological reliability. Its agricultural potential is therefore constrained less by the absence of water than by the strong seasonal imbalance between water inputs and losses. Sustainable development should prioritize seasonal storage, regulated abstraction, efficient irrigation, protection of inflow channels, and designated livestock watering facilities. The study demonstrates the importance of integrating hydro-morphometric characteristics with water-budget analysis when evaluating the agricultural potential of small wetlands in seasonally water-limited environments.

KEYWORDS

Hydro-morphometric, water budget, wetland hydrology, water storage, seasonal water availability, irrigation, livestock production, Lake Ruma, Nigeria

I. INTRODUCTION

Wetlands are dynamic hydrological systems whose ecological functions and productive capacity are governed by interactions among water availability, storage, movement, and seasonal variability (Mitsch & Gosselink, 2015; Convention on Wetlands, 2025). They regulate surface-water flows, enhance groundwater interactions, moderate floods, retain nutrients, and provide essential resources for surrounding communities. Beyond their ecological significance, wetlands contribute directly to agricultural production by supporting irrigation, livestock watering, fisheries, and dry-season cultivation, particularly in regions where rainfall is highly seasonal and freshwater availability is limited. However, the relationship between wetlands and agriculture is complex because agricultural intensification can simultaneously benefit from and threaten the hydrological processes that sustain wetland productivity. Sustainable agricultural development in wetland environments therefore requires approaches that consider both resource availability and the maintenance of hydrological functions.

The agricultural potential of a wetland cannot be determined solely by the presence of surface water. Water availability for production depends on the capacity of the wetland to store, retain, and release water over time. A wetland may contain substantial water during the rainy season but experience rapid depletion during subsequent dry periods due to limited storage capacity, high evaporative losses, or reduced inflow. Thus, assessments based only on observed water presence or maximum storage conditions may overestimate the reliability of water resources for irrigation and livestock production. Understanding wetland agricultural potential therefore requires evaluation of both physical storage capacity and temporal hydrological reliability.

Hydro-morphometric characteristics provide the foundation for understanding the physical controls of wetland water storage. Parameters such as surface area, basin geometry, depth distribution, shoreline configuration, and storage volume determine the amount of water retained within a wetland and influence its sensitivity to seasonal climatic variation. Depth is particularly important because shallow systems generally experience greater evaporative losses due to high surface-area-to-volume ratios, whereas deeper systems possess greater capacity to buffer short-term fluctuations in water availability. Although hydro-morphometric studies have improved understanding of wetland structure and ecological functioning, their application to agricultural water-resource assessment remains limited.

Hydro-morphometric information alone, however, provides only a static representation of wetland water resources. The sustainability of agricultural use depends on the balance between hydrological inputs and losses over time. Water-budget analysis provides an effective approach for quantifying this temporal dimension by integrating precipitation, inflow, evapotranspiration, seepage, outflow, and abstraction. Positive water balances indicate storage recovery, whereas persistent deficits indicate declining water availability and potential constraints to agricultural production. This distinction is particularly important in semi-arid and seasonally dry environments where evaporation frequently exceeds rainfall during extended dry periods.

Large African wetland systems demonstrate the importance of seasonal hydrological variability in controlling ecosystem productivity and human resource use. The flood pulse concept proposed by (Junk et al. 1989)) provides a fundamental framework for understanding how periodic variations in water level, lateral connectivity, and inundation duration regulate ecological processes and resource availability in river–floodplain systems. In the Sudd Wetland, seasonal inundation regulates hydrological connectivity, ecological processes, and spatial water distribution, while evaporation strongly influences flood persistence. Similarly, studies of the Inner Niger Delta have demonstrated substantial temporal variation in flood extent and water storage, highlighting the importance of seasonal dynamics in determining resource availability. Research in the Okavango Delta has further shown that wetland functioning depends on interactions between upstream inflows, local rainfall, evaporation, and floodplain storage processes. Small tropical wetlands represent a particularly important but understudied component of agricultural water systems. Unlike large floodplain wetlands with substantial storage capacity and complex hydrological networks, smaller wetlands often have limited buffering capacity and are more vulnerable to seasonal water deficits. In many rural regions of Africa, these systems provide critical water sources for smallholder irrigation and livestock production, yet their hydrological characteristics remain poorly quantified. The absence of detailed hydro-morphometric and water-budget information limits the ability of resource managers to determine whether current agricultural use is sustainable or whether additional interventions, such as water harvesting and storage enhancement, are required.

Existing wetland assessments have increasingly applied remote sensing, GIS-based suitability analysis, and multi-criteria decision approaches to evaluate agricultural potential. However, many studies emphasize land characteristics, vegetation conditions, or water quality while giving limited consideration to the interaction between storage capacity and seasonal water availability. Similarly, hydro-morphometric investigations and water-budget studies have generally developed independently, resulting in a fragmented understanding of how physical storage characteristics influence hydrological reliability. This limitation is particularly evident in small tropical wetlands where long-term hydrological monitoring is scarce and agricultural decisions are often based on seasonal water availability rather than quantitative assessment.

Lake Ruma Wetland, located in Song Local Government Area of Adamawa State, north-eastern Nigeria, represents such a system. The wetland supports irrigation activities, livestock production, and other livelihood functions within surrounding communities. It receives water from direct rainfall, surface runoff, seasonal inflows, and floodplain connectivity associated with the River Kilange system. Despite its local importance, quantitative information regarding its hydro-morphometric characteristics, storage capacity, and seasonal water reliability remains limited. This knowledge gap creates uncertainty regarding the extent to which existing agricultural use reflects sustainable water availability.

This study addresses this limitation by integrating field-based hydro-morphometric measurements with seasonal water-budget analysis to evaluate the agricultural water potential of Lake Ruma Wetland. Unlike previous studies that have examined wetland morphology or hydrological processes separately, this research evaluates their combined influence on irrigation and livestock water availability. The study aims to:

- characterize the hydro-morphometric properties of Lake Ruma Wetland;
- estimate water-storage capacity from measured surface area and depth characteristics;
- evaluate hydrological connectivity and dominant water sources;
- quantify seasonal and annual water-budget variability; and
- Determine the implications of storage characteristics and water availability for sustainable agricultural use.

The central hypothesis of this study is that wetland agricultural potential is determined not by water volume alone, but by the interaction between storage capacity, hydrological variability, and seasonal water persistence. By integrating these dimensions, the study provides a transferable framework for evaluating small tropical wetlands where agricultural demand is increasing but hydrological information remains limited.

II. MATERIALS AND METHODS

A. Study Area

Lake Ruma Wetland is located in Song Local Government Area of Adamawa State, north-eastern Nigeria, within the Sudan Savanna ecological zone. The wetland and its immediate surroundings occupy approximately 3.39 km² and lie between latitudes 09°31′30″ N and 09°43′30″ N and longitudes 12°40′00″ E and 12°44′30″ E. The wetland is situated approximately 15 km southeast of Song town on the right-bank floodplain of the River Kilange, south of Wuro Daudu settlement, within the lower Kilange Trough.

Lake Ruma receives water from several sources. These include direct rainfall, perennial and seasonal stream inflows, seasonal overflow from the Kilange River, and surface runoff from the surrounding catchment. Field observations identified Dalong Stream as a principal perennial inflow, while seasonal overflow from the Kilange River contributes additional recharge during periods of high rainfall and river discharge. The wetland also contains interconnected channels, shallow depressions, and seasonally inundated areas that facilitate the redistribution of water across the wetland landscape. The surrounding communities are primarily engaged in agriculture and livestock production. The wetland therefore represents an important local water resource whose hydrological reliability has direct implications for agricultural planning and livelihood sustainability. See figure 1

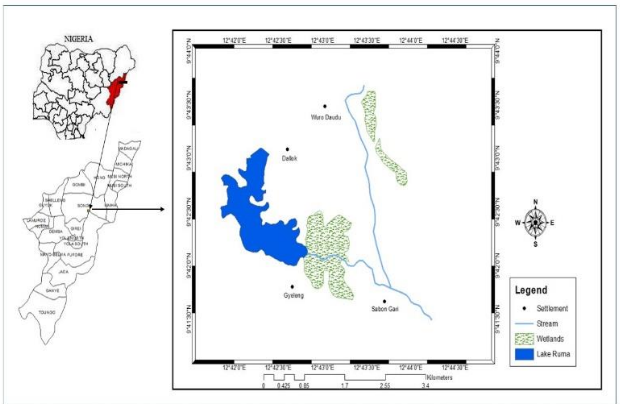

Figure 1. Location and drainage setting of Lake Ruma Wetland, Song Local Government Area, Adamawa State, Nigeria.

B. Research Design

The study adopted an integrated field-based and geospatial research design. Hydro-morphometric measurements were combined with spatial analysis, bathymetric observations, digital elevation model processing, and long-term water-budget analysis.

The methodological framework was designed to establish the relationship between:

Wetland Morphology → Storage Capacity → Hydrological Variability → Agricultural Water Reliability

The analysis therefore combined static measurements of the wetland's physical dimensions with temporal assessment of water inputs and losses.

C. Data Sources

1. Primary Data

Primary hydro-morphometric data were obtained through:

- GPS survey of the wetland boundary;
- Field measurements of maximum length and width;
- Bathymetric measurements of water depth;
- Field observations of inflow and drainage channels;
- Observations of seasonally inundated areas; and
- Identification of water-retention zones and hydrological connections.

A Garmin eTrex 20 GPS was used to record boundary and spatial reference coordinates, while bathymetric depth measurements were obtained with field-based depth-measurement equipment.

2. Secondary Data

Secondary data included:

- Long-term hydrological records;
- Rainfall data from the Nigerian Meteorological Agency (NiMet);
- Evapotranspiration-related data;
- Digital Elevation Model data for watershed and drainage analysis; and
- Relevant spatial datasets used to characterize the wetland's drainage environment.

The water-budget analysis was based on a 30-year hydrological record.

D. Hydro-Morphometric Survey

The hydro-morphometric survey involved measuring the principal physical characteristics of Lake Ruma Wetland.

1. Surface Area and Basin Dimensions

GPS coordinates collected around the wetland boundary were imported into a GIS environment and used to delineate the open-water area. The maximum length and maximum width were determined from the digitized wetland geometry.

2. Depth Measurement

Water-depth observations were collected at representative locations across the wetland. Mean depth was calculated as:

$$\overline{Z} = \frac{\sum_{i=1}^{n} d_i}{n}$$

Where:

- $\overline{Z}$ = mean depth (m);
- d = sum of measured depth values (m); and
- n = number of depth observations.

3. Water Volume

Estimated water volume was calculated from surface area and mean depth:

$$V = A \times \overline{Z}$$

Where:

- V = estimated water volume (m3)
- A = surface area (m2)
- $\overline{Z}$ = mean depth (m)

The resulting volume represents an estimated storage volume based on the measured open-water area and mean depth. It should therefore be interpreted as a field-based storage estimate rather than a complete stage–area–volume curve.

E. Watershed and Drainage Analysis

A Shuttle Radar Topography Mission Digital Elevation Model was processed using GIS-based hydrological tools. The processing sequence included:

- Sink filling;
- flow-direction analysis;
- flow-accumulation analysis;
- watershed delineation;
- drainage-network extraction; and
- Interpretation of contributing runoff pathways.

The resulting drainage network was integrated with field observations to identify the principal inflow pathways and the hydrological connections between Lake Ruma, the River Kilange, Dalong Stream, and the surrounding catchment.

F. Water-Budget Analysis

The hydrological water budget was represented using:

$\Delta S = P + Q_{in} - ET - Q_{out}$

Where:

- ΔS = Change in water storage (m^3 or mm)
- P = Direct precipitation falling on the wetland (mm)
- Q_{in} = Surface runoff/inflow from the contributing watershed (mm or m^3)
- ET = Actual evapotranspiration loss (mm)
- Q_{out}= Surface water outflow from the wetland (mm or m^3).

Positive values represented net water accumulation, whereas negative values represented net depletion.

The climatic water balance was also expressed as:

$WB=P-PET$ (7)

Where:

- WB = climatic water balance (mm);
- P = precipitation (mm); and
- PET = potential evapotranspiration (mm).
- The results were interpreted as:
- WB>0 = water surplus
- WB=0 = water equilibrium
- WB<0 = water deficit

Monthly and annual water-balance values were summarized using the mean, standard deviation, minimum, maximum, and coefficient of variation.

The coefficient of variation was calculated

$$CV = \frac{\sigma}{x} \times 100$$

Where

- CV = Coefficient of Variation (%)
- sigma = Standard Deviation
- x = Mean

G. Annual Inflow and Outflow Analysis

Annual inflow and outflow were summarized to assess the long-term relationship between water gains and losses.

The annual net balance was calculated as:

$$NB = I - O$$

Where:

- NB = net annual water balance;
- I = annual inflow; and
- O = annual outflow.

The frequency of deficit and surplus years was also determined.

III. RESULTS

A. Hydrological Connectivity and Sources of Water

Field observations indicated that Lake Ruma Wetland is hydrologic ally connected to its surrounding drainage environment through several water pathways. Dalong Stream was identified as a principal perennial inflow channel, providing water throughout the year. Seasonal overflow from the Kilange River provides additional recharge during periods of high rainfall and increased river discharge. Direct rainfall contributes water directly to the wetland surface, while runoff from the surrounding catchment provides additional seasonal inflow.

The wetland contains interconnected channels, shallow depressions, and seasonally inundated floodplain areas. These features facilitate the lateral redistribution of water and create spatial variation in hydro period. Consequently, the wetland consists of a permanent or semi-permanent open-water component and seasonally inundated peripheral areas.The observed hydrological connectivity demonstrates that Lake Ruma is not an isolated water body. Its water availability is influenced by processes occurring within the wider catchment, including rainfall, runoff generation, channel flow, and seasonal river overflow.

B. Hydro-Morphometric Characteristics

The hydro-morphometric survey showed that Lake Ruma Wetland has an elongated and relatively shallow morphology.

Table 1. Hydro-morphometric characteristics of Lake Ruma Wetland

Parameter	Value
Maximum length	2.18 km
Maximum width	0.59 km
Open-water surface area	1.52 km²

Maximum depth	2.23 m
Mean depth	0.97 m
Estimated water volume	1.47 million m³

The maximum length of 2.18 km compared with the maximum width of 0.59 km indicates a longitudinally elongated basin configuration. The open-water surface area was 1.52 km². The maximum recorded depth was 2.23 m, while the mean depth was 0.97 m. The difference between the maximum and mean depth indicates substantial spatial variation in bathymetry. Deeper water was concentrated in the central open-water sections, whereas shallower conditions occurred along the wetland margins and in seasonally inundated zones.

The estimated water volume was approximately 1.47 million m³. This indicates appreciable physical storage capacity, although the relatively shallow mean depth suggests considerable sensitivity to evaporation, water abstraction, and seasonal reductions in inflow.

C. Spatial Distribution of Water-Depth Conditions and Wetland Vegetation

The spatial distribution of water depth revealed distinct hydrological zones within the wetland. The central open-water sections contained the deepest water, while the margins were generally shallow and more seasonally variable.

The shallow marginal zones supported extensive aquatic and wetland vegetation. Water lily (Nymphaea spp.) and cattail (Typha angustifolia) were among the dominant macrophytes observed. Vegetation density was generally higher in shallow areas and along wetland margins, while deeper permanently inundated sections supported dense aquatic vegetation. The distribution of vegetation corresponded to variations in water depth and hydroperiod, demonstrating the relationship between wetland morphology and ecological structure. See Figure 2

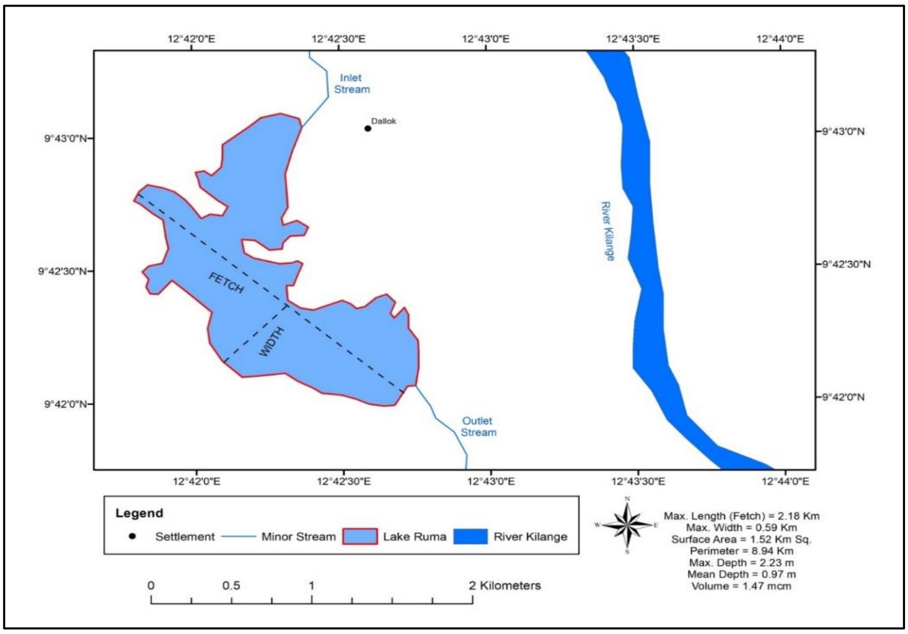

Figure 2. Hydro-morphometric of Lake Ruma Wetland

D. Monthly Water-Budget Dynamics

The monthly water-budget analysis demonstrated strong seasonal variation in water availability. Negative water-balance conditions occurred during most months of the year. Mean monthly deficits ranged from −21.22 mm in June to −258.20 mm in January.

The largest mean deficits were recorded in:

- January: −258.20 mm;
- April: −249.98 mm;
- March: −243.63 mm; and
- November: −204.66 mm.

Positive mean water-balance conditions occurred only during July, August, and September.

Table 2. Monthly water-balance statistics for Lake Ruma Wetland

Month	**n**	**Mean balance (mm)**	**SD (mm)**	**Minimum (mm)**	**Maximum (mm)**
January	4	−258.20	219.58	−587.16	−133.72
February	4	−165.14	5.82	−170.10	−156.75
March	11	−243.63	40.39	−294.10	−148.83
April	30	−249.98	42.13	−319.71	−169.53
May	29	−93.32	66.57	−264.20	28.87
June	30	−21.22	66.89	−130.38	119.12
July	30	102.58	332.79	−60.80	1,836.02
August	30	82.20	69.60	−20.42	328.74
September	30	64.73	70.33	−49.66	210.82
October	30	−83.47	59.68	−162.23	53.20
November	8	−204.66	167.85	−611.57	−90.67
December	4	−134.58	15.16	−146.45	−112.47

July recorded the highest mean surplus at 102.58 mm and the greatest variability, with a standard deviation of 332.79 mm. The maximum observed July surplus was 1,836.02 mm, indicating the potential for substantial episodic water accumulation during high-inflow events.

August and September recorded mean surpluses of 82.20 and 64.73 mm, respectively. See Figure 3

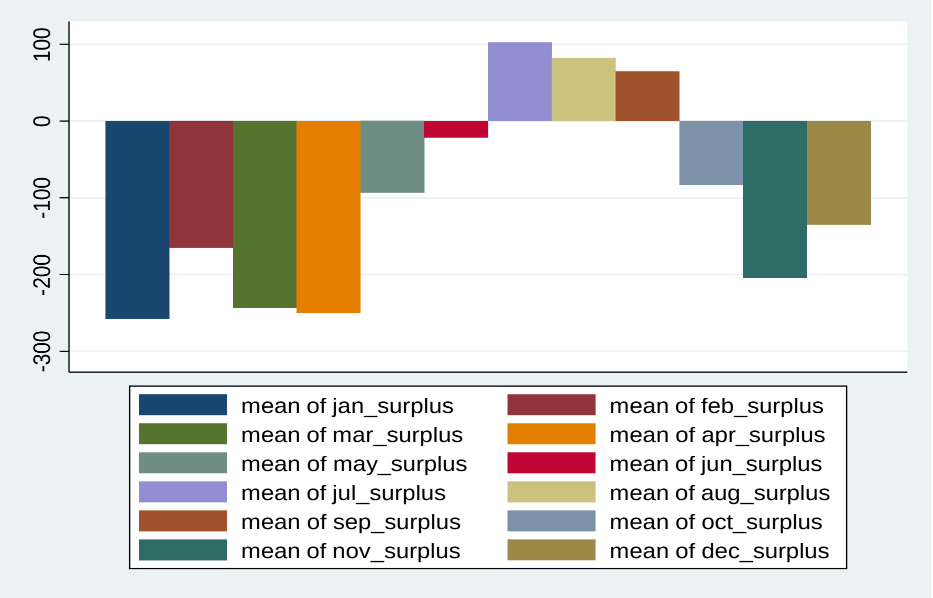

Figure 3. Monthly water-balance dynamics of Lake Ruma Wetland

E. Annual Inflow and Outflow Characteristics

The annual water-budget analysis demonstrated a persistent long-term imbalance between water inflows and outflows.

Table 3. Annual inflow and outflow statistics for Lake Ruma Wetland

Variable	**Mean (mm)**	**SD (mm)**	**Minimum (mm)**	**Maximum (mm)**
Annual inflow	289.18	340.89	75.60	2,007.69
Annual outflow	702.84	318.43	290.59	1,738.35

The mean annual outflow exceeded the mean annual inflow by:

702.84-289.18 = 413.66 mm

This produced a mean annual deficit of approximately 413.66 mm.

The ratio of mean annual outflow to inflow was approximately:

702.84/289.18=2.43

Thus, mean annual water losses were approximately 2.4 times greater than mean annual inflows.

The annual water-balance values ranged from a minimum deficit of −1,519.17 mm to a maximum surplus of +1,337.16 mm.

F. Frequency of Annual Water Deficit and Surplus

Out of the 30 years analysed:

28 years (93.33%) recorded annual water deficits;

2 years (6.67%) recorded annual water surpluses.

Table 4. Frequency of annual water-balance conditions

Condition	**Number of years**	**Percentage**
Annual deficit	28	93.33%
Annual surplus	2	6.67%
Total	30	100.00%

The dominance of deficit years indicates that Lake Ruma operates under a structurally water-limited hydrological regime. Although substantial seasonal surpluses occur during the main rainy season, these are insufficient to offset the cumulative annual losses in most years.

IV. DISCUSSION

A. Hydro-Morphometric and the Physical Basis of Water Storage

The hydro-morphometric characteristics of Lake Ruma demonstrate that the wetland possesses an appreciable physical water-storage resource. The open-water surface area of 1.52 km^2 and estimated volume of 1.47 million m^3 represent a substantial localized water resource for a rural wetland system.

However, the importance of these measurements lies not only in their absolute magnitude but in their relationship to the geometry and depth of the wetland. The elongated configuration of Lake Ruma suggests that water movement is influenced by the longitudinal organization of the wetland and its connections to inflowing channels. The relatively shallow mean depth of 0.97 m, in contrast with a maximum depth of 2.23 m, indicates that water storage is spatially uneven.

This spatial heterogeneity has direct implications for agricultural water use. Deeper central sections are likely to retain water longer during periods of declining inflow, while shallow marginal areas are more vulnerable to evaporation and seasonal drying. Consequently, a single estimate of total water volume may overstate the amount of water that is practically available for abstraction at all times.

This finding reinforces the importance of integrating area, depth, and volume measurements rather than relying on a single hydro-morphometric indicator. The physical water resource of Lake Ruma is therefore best understood as a spatially differentiated storage system.

B. Hydrological Connectivity and the Flood-Pulse Principle

The presence of multiple inflow pathways demonstrates that Lake Ruma is functionally connected to the wider catchment. Direct rainfall, Dalong Stream, seasonal Kilange River overflow, and surface runoff all contribute to the wetland water regime.

This hydrological connectivity is consistent with the broader flood-pulse principle observed in major African wetlands. In the Sudd, seasonal inundation is a fundamental driver of hydrological and ecological processes, while the spatial distribution of flooding and evaporation changes throughout the annual cycle (Rebelo et al., 2012). The Inner Niger Delta similarly exhibits substantial temporal variability in inundated area and surface-water volume, with seasonal hydrology strongly influencing the extent and persistence of water across the wetland system (Bergé-Nguyen & Crétaux, 2015; Normandin et al., 2024).

Lake Ruma operates at a much smaller spatial scale than these major African wetlands, but the underlying hydrological principle is comparable. Water is accumulated during periods of high rainfall and inflow and subsequently redistributed and depleted during periods of reduced input and increased atmospheric demand.

The major difference is buffering capacity. A small, shallow wetland has less capacity to absorb prolonged hydrological deficits than a large floodplain system. Therefore, the consequences of annual water deficits may be more rapidly transmitted to irrigation and livestock users at Lake Ruma.

C. Seasonal Water Surplus and the Timing of Agricultural Opportunity

The concentration of positive water-balance conditions in July–September is one of the most important findings of the study.

This three-month period represents the principal seasonal recharge window for Lake Ruma. During this period, rainfall, runoff, and inflow are sufficient to exceed water losses. The result is an increase in water availability and likely expansion of wetland inundation.

The concentration of recharge within a short period has important implications for agricultural planning. The surplus period should be regarded as an opportunity for:

- Wetland recharge;
- Water storage;
- Irrigation-water harvesting;
- Replenishment of livestock watering points; and
- Recovery of water levels following preceding deficit conditions.

However, the surplus should not automatically be interpreted as water that can be entirely abstracted for agriculture. Wetland hydrological processes and ecological functions depend on the persistence of water and the continuation of seasonal inundation.

The appropriate management principle is therefore to capture a proportion of seasonal surplus while maintaining sufficient water for wetland ecological processes.

D. Persistent Annual Deficits and Hydrological Reliability

The annual water-budget analysis provides a stronger indication of long-term water reliability than the monthly surplus pattern alone.

The mean annual inflow was 289.18 mm, while mean annual outflow was 702.84 mm. The resulting deficit of 413.66 mm demonstrates that annual losses substantially exceed annual gains.

The fact that 28 of 30 years recorded annual deficits is particularly important. It indicates that the wetland's hydrological regime is not characterized by occasional deficits caused by unusual drought years. Rather, deficit conditions are structurally dominant.

This finding has a direct implication for irrigation development: the presence of substantial water storage does not guarantee long-term water security.

The water resource must be managed according to the rate of replenishment and the expected duration of storage. Without storage infrastructure and controlled abstraction, water availability may decline progressively following the July–September recharge period.

The result also explains why the hydro-morphometric potential of Lake Ruma cannot be evaluated using water volume alone. A wetland may have 1.47 million m^3 of estimated water volume and still have limited capacity to support continuous year-round abstraction if annual losses substantially exceed inflows.

E. Comparison with Other African Wetland Systems

The Lake Ruma results are consistent with the broader hydrological behaviour observed in African wetlands, although the scale and magnitude differ considerably.

In the Sudd, seasonal inundation and evaporation create pronounced changes in the spatial distribution and persistence of water. The hydrological system is strongly dependent on the annual flood pulse.

In the Inner Niger Delta, surface-water extent and volume also vary substantially over time, reflecting the influence of seasonal inflow and flood dynamics.The similarity between Lake Ruma and these larger systems is therefore conceptual rather than quantitative. All are characterized by:

- Seasonal hydrological pulses;
- Spatially variable water storage;

- Dependence on inflow and precipitation;
- Evaporation and other water losses; and
- Strong temporal variation in water availability.

The difference is that Lake Ruma has much smaller storage capacity and therefore less hydrological buffering. This makes it particularly important to integrate water-budget information into local agricultural planning.

F. Implications for Irrigation Development

The results suggest that Lake Ruma can support irrigation development, but such development should be appropriately scaled and hydrologic ally regulated.

The most important management concern is the mismatch between the physical volume of water and the long-term water budget. The estimated volume of 1.47 million m³ indicates a substantial water resource, but the predominance of annual deficits suggests that continuous abstraction could progressively reduce storage.

Irrigation development should therefore be based on:

- Seasonal water availability;
- Available storage;
- expected inflow;
- Crop-water requirements;
- Ecological water requirements; and
- The anticipated duration of the dry-season deficit.

The July–September surplus period provides an opportunity for water harvesting and storage. Small reservoirs, farm ponds, off-channel storage structures, and rainwater-harvesting systems could increase the availability of water during subsequent deficit periods.

Efficient irrigation systems should also be promoted to reduce water losses. Where feasible, water-saving irrigation methods should be prioritized over inefficient systems that increase conveyance and application losses.

The management objective should therefore not be to maximize water abstraction but to increase the efficiency with which seasonal water availability is converted into agricultural production.

G. Implications for Livestock Production

The hydrological characteristics of Lake Ruma also have implications for livestock production.

The persistence of water in principal channels and natural depressions during the dry season indicates that certain parts of the wetland may provide relatively reliable livestock watering points. However, unrestricted livestock access can damage wetland margins, increase bank erosion, disturb aquatic vegetation, and contribute to water contamination.

Designated watering points should therefore be established at suitable locations with stable access conditions. Such facilities would help concentrate livestock activity and reduce degradation across sensitive wetland margins.

The seasonal water budget also suggests that livestock-water planning should account for declining water availability during prolonged deficit periods. During these periods, supplementary water infrastructure may be required to prevent excessive pressure on the wetland's remaining water-retention zones.

H. Catchment Degradation and the Future of Wetland Storage

The physical storage capacity of Lake Ruma is directly connected to the condition of the surrounding catchment.

Deforestation, soil erosion, agricultural expansion, and poor land-use practices may increase sediment delivery to inflow channels and the wetland basin. Sedimentation can reduce effective depth and storage capacity, thereby worsening the effects of seasonal water deficits.

This is particularly important because Lake Ruma is already relatively shallow. Even moderate sediment accumulation may reduce storage volume and alter the hydrological connectivity between the wetland and its inflow channels.

The environmental challenges identified elsewhere in the broader Lake Ruma assessment, including deforestation, erosion, and inadequate conservation, therefore have direct implications for the hydro-morphometric component.

Catchment management should consequently be regarded as a water-storage intervention. Reforestation, riparian-buffer protection, erosion control, and the stabilization of drainage channels can help maintain inflow pathways and reduce sedimentation.

I. Implications for Integrated Wetland Agricultural Planning

The findings of this study demonstrate that hydro-morphometric characteristics and water-budget dynamics should be integrated when assessing wetland agricultural potential. While hydro-morphometric analysis provides information on the physical capacity of a wetland to store water, water-budget analysis evaluates the reliability and sustainability of that water supply over time. Therefore, both approaches provide complementary information that is essential for effective agricultural planning.

Hydro-morphometric analysis primarily addresses the question: How much water can the wetland physically store? This assessment considers important physical attributes such as surface area, water depth, storage volume, and channel characteristics. These parameters provide an understanding of the available water resource and the potential capacity of the wetland to support agricultural activities. For instance, a wetland with a large surface area, appreciable water volume, permanent channels, and deeper storage zones may initially appear suitable for irrigation development because of its apparent water availability.

However, physical storage capacity alone does not determine the sustainability of agricultural water use. Water-budget analysis addresses a different but equally important question: How reliable is that water supply over time? By examining the relationship between inflows and losses, including rainfall, runoff, evaporation, evapotranspiration, seepage, and water abstraction, water-budget analysis reveals whether the wetland can maintain adequate water availability throughout different seasons. A wetland may possess substantial storage capacity, but if annual water losses consistently exceed inflows, its ability to support continuous irrigation may become constrained, particularly during prolonged dry periods.

The Lake Ruma case illustrates this important distinction. Although the wetland possesses measurable water storage capacity, the water-budget assessment revealed considerable seasonal variability, with water deficits occurring during most months and surplus conditions occurring only during the peak rainy season. This indicates that the wetland has the physical capacity to support agricultural activities but requires appropriate water-management strategies to overcome seasonal limitations. Therefore, agricultural planning based solely on water volume or wetland size may overestimate its long-term irrigation potential.

The integration of hydro-morphometric and water-budget analyses provides a more comprehensive understanding of wetland water resources by combining information on water quantity and water reliability. Water quantity describes the amount of water available at a particular time, whereas water reliability reflects the capacity of the wetland to sustain that availability under seasonal and climatic variations. Both factors are critical because sustainable irrigation depends not only on the presence of water but also on its continued availability during periods of high agricultural demand.

This integrated approach has important implications for Lake Ruma's agricultural development. Although the wetland provides valuable opportunities for irrigation and livestock production, its seasonal water deficit suggests the need for adaptive water-management interventions. These may include small-scale water storage structures, rainwater harvesting, off-channel reservoirs, improved irrigation scheduling, and controlled water abstraction during dry periods. Such interventions would enhance water security while reducing pressure on the wetland ecosystem.

The findings also support a broader principle of wetland agricultural assessment: wetland potential should be evaluated based on both water storage capacity and temporal water availability. This perspective moves beyond conventional assessments that focus mainly on the physical presence of water and recognizes the importance of seasonal dynamics in determining agricultural sustainability. This principle aligns with recent agricultural water-management perspectives, which emphasize that increasing agricultural demand is occurring under conditions of increasing uncertainty in water availability due to climate variability and competing water uses (FAO, 2024).

Furthermore, the findings are consistent with contemporary wetland management principles, which emphasize balancing agricultural production with the conservation of wetland ecological functions (Convention on Wetlands, 2025). Wetlands provide multiple ecosystem services, including biodiversity conservation, flood regulation, groundwater recharge, and livelihood support. Consequently, agricultural development within Lake Ruma should adopt an integrated management approach that promotes productive use of wetland resources while maintaining ecological sustainability.

Overall, the integration of hydro-morphometric and water-budget analyses provides a stronger scientific basis for evaluating wetland agricultural potential. The Lake Ruma assessment demonstrates that a wetland may possess considerable water storage capacity but still experience limitations in sustaining agricultural production if seasonal water deficits are not addressed. Therefore, effective wetland agricultural planning requires consideration of both the quantity of available water and the reliability of that water supply over time.

V. CONCLUSION

This study assessed the hydro-morphometric characteristics and water-budget dynamics of Lake Ruma Wetland and examined their implications for irrigation and livestock production. Lake Ruma possesses an elongated and relatively shallow morphology, with a maximum length of 2.18 km, maximum width of 0.59 km, open-water surface area of 1.52 km², maximum depth of 2.23 m, mean depth of 0.97 m, and estimated water volume of approximately 1.47 million m³.

The wetland is hydrologic ally connected to its surrounding catchment through direct rainfall, perennial stream inflow, seasonal river overflow, and surface runoff. This connectivity supports seasonal water replenishment and redistribution.

However, the water-budget analysis demonstrated strong seasonal and annual limitations. Positive monthly water-balance conditions were restricted to July–September, while mean annual outflow exceeded mean annual inflow by 413.66 mm. Annual deficits occurred in 28 of the 30 years analysed. The findings demonstrate that Lake Ruma possesses substantial physical water-storage capacity but limited year-round hydrological reliability. The principal constraint to agricultural development is therefore not the absence of water but the seasonal and annual imbalance between water gains and losses.

Lake Ruma can support irrigation and livestock production, but agricultural development should remain within the hydrological capacity of the wetland. The most appropriate management strategy is one based on seasonal storage, regulated abstraction, efficient water use, protection of catchment and inflow systems, and maintenance of ecological water requirements.

A. Management Implications, Limitations, and Future Research Directions

The hydro-morphometric and water-budget assessment of Lake Ruma provides important implications for sustainable wetland agricultural planning. Although the wetland possesses measurable storage capacity and supports irrigation and livestock activities, the observed seasonal variation in water availability indicates that agricultural expansion should be accompanied by appropriate water-management interventions. The findings demonstrate that wetland agricultural potential depends not only on the quantity of stored water but also on the reliability of water availability throughout the year.

The occurrence of water surplus conditions during the July–September period presents an opportunity for improving dry-season water security through strategic water-storage interventions. Small-scale reservoirs, farm ponds, off-channel storage facilities, and rainwater-harvesting systems could be developed to capture part of the seasonal surplus and provide supplementary water during periods of deficit. Such interventions would reduce pressure on the wetland during dry months while improving the reliability of irrigation supply. However, storage development should be carefully planned to maintain natural hydrological processes and ecological functions.

The seasonal water deficit identified in this study further highlights the need for regulated irrigation abstraction. Water withdrawal from Lake Ruma should be guided by water-level conditions, available storage, seasonal inflows, projected agricultural demand, and ecological water requirements. Implementing controlled abstraction strategies would prevent excessive exploitation of wetland water resources and support long-term agricultural sustainability.

Improving irrigation efficiency is also essential for reducing water losses during deficit periods. The promotion of water-saving irrigation technologies, improved scheduling practices, and efficient conveyance systems would enhance the productivity of available water resources. These measures are particularly important in semi-arid environments where agricultural demand is increasing while water availability remains seasonally uncertain.

Maintaining the hydrological connectivity of the wetland is equally important. Inflow pathways, including Dalong Stream and seasonal drainage channels, should be protected from blockage, excessive sedimentation, and inappropriate land-use alteration. Catchment conservation practices, including vegetation restoration, riparian-buffer protection, erosion control, and improved land-use management, are recommended to reduce sediment delivery and maintain the storage capacity of the wetland.

Livestock management also requires consideration within the wetland system. Although livestock production is an important livelihood activity, uncontrolled access to water bodies may contribute to shoreline degradation, bank erosion, sediment disturbance, and deterioration of water quality. Establishing designated livestock-watering points would minimize environmental impacts while maintaining livestock access to essential water resources.

Despite providing a baseline assessment of Lake Ruma’s hydro-morphometric characteristics and water-budget dynamics, this study has some limitations. The estimated water volume was derived from measured surface area and mean depth; therefore, a detailed bathymetric survey with higher spatial resolution would improve storage estimates and enable the development of a stage–area–volume relationship. In addition, the accuracy of the water-budget assessment is influenced by the availability and temporal consistency of hydrological data. Future investigations should incorporate direct measurements of stream discharge, evaporation, groundwater exchange, abstraction rates, and sedimentation processes to improve the estimation of individual water-budget components.

Future research should also integrate hydrological modelling with remote sensing techniques to monitor long-term changes in wetland extent, inundation patterns, and storage dynamics. Satellite-based observations combined with field measurements would improve understanding of the relationship between water level, surface-water area, and storage variation, thereby providing a stronger basis for sustainable irrigation planning and wetland conservation.

Overall, the Lake Ruma assessment demonstrates that hydro-morphometric capacity alone does not adequately define wetland agricultural potential. Integrating physical storage characteristics with seasonal water-budget dynamics provides a more reliable framework for evaluating agricultural suitability and developing management strategies that balance irrigation development with wetland ecological sustainability.

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