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Spatial Analysis of Surface Water Potential for Hydro-Agricultural Development: Application to the Nanija Bolong Watershed (Senegal)

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Abstract

Surface-water availability is a key determinant of hydro-agricultural development in Sudano-Sahelian watersheds, where stream flow is highly seasonal and natural or engineered storage is unevenly distributed. This paper examines the spatial potential of surface-water resources in the Nanija Bolong watershed, Kaffrine Region, Senegal, to support hydro-agricultural planning. The approach integrates topographic, hydrographic, satellite and field data, mainly covering 1981–2024. The drainage network is derived from a 30-m SRTM digital elevation model using standard hydrological processing and complemented with Sentinel-2 imagery, OpenStreetMap hydrography, national water-resource inventories and GPS field observations. Temporary ponds, valley bottoms, alluvial valleys, depressions and temporary water-storage areas are mapped by combining terrain attributes, flow accumulation, satellite-derived wetness indicators and field evidence. Available thesis results indicate that the Nanija Bolong is the main drainage axis, extending for approximately 208 km. Flows are concentrated mainly between June and October, while many channels become temporarily dry during the dry season. Ponds, valley bottoms and reservoirs, including the Mérato North and South retention basins, contribute to temporary storage and support livestock watering, market gardening and some domestic uses. In the thesis multi-criteria framework, surface-water resources account for 25% of the hydro-agricultural potential index. The study emphasizes the need to assess water occurrence together with storage duration, water volumes, water quality, soil suitability, erosion risk, accessibility and ecological constraints before selecting development sites.

Keywords: *surface water; spatial analysis; GIS; remote sensing; drainage network; temporary ponds*

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1. Introduction

In the Sudanian-Sahelian regions, surface water is a strategic resource for agricultural and pastoral systems, livestock feed, and ecosystem functioning. However, its availability is highly seasonal and depends on both the quantity and temporal distribution of rainfall, as well as the physical characteristics of the watersheds. Ponds, depressions, and small temporary bodies of water can fill during the rainy season and then shrink or dry up during the dry season. This dynamic is particularly pronounced in Sahelian environments where water resources exhibit high intra- and interannual variability (Haas et al., 2009; Haas et al., 2011). Furthermore, the work of Gardelle et al. (2010) shows that changes in water surface area do not depend solely on rainfall totals: soil properties, topography, vegetation, and runoff conditions also influence the hydrological response of ponds.

This seasonality poses a major constraint on securing agro-pastoral activities. Knowledge of the location, permanence, accessibility, and storage capacity of water resources is essential for planning small-scale irrigation, developing lowland areas, watering livestock, and certain domestic uses. Temporary ponds play a significant role in the livelihoods of rural Sahelian communities, but monitoring them remains difficult due to their dispersed nature, intermittent occurrence, and the inadequacy of ground-based monitoring networks (Herndon et al., 2020; USGS, 2025). It is nevertheless important to distinguish between the apparent presence of a water surface and the actual availability of a usable resource: a satellite image alone cannot determine the depth, stored volume, water quality, or retention time.

Advances in remote sensing and geographic information systems (GIS) offer significant opportunities for inventorying hydrographic networks, identifying topographic depressions, mapping wetlands, and monitoring changes in water surface area. Digital terrain models (DTMs) allow for the characterization of flow directions, flow accumulation, and topographic features conducive to runoff concentration (Jenson and Domingue, 1988; Tarboton , 1997). Multispectral optical imagery , for its part, allows for the differentiation of water surfaces based on their spectral responses and dedicated indices. In northern Senegal, Soti et al. (2009) demonstrated the value of indices incorporating the mid-infrared, particularly the MNDWI, for mapping temporary ponds. However, Herndon et al. (2020) emphasize that global products may underestimate small, turbid water bodiesin the Sahel and that methods must be adapted to local conditions. The integration of satellite, topographic, hydrographic data and field observations therefore appears essential to improve the reliability of inventories.

The Nanija Bolong watershed, located in the Kaffrine region of central Senegal, is situated within the Sudano-Sahelian context where surface water resources are subject to strong seasonality. Its hydrological

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functioning is governed by the alternation between the rainy and dry seasons. The hydrographic network is organized around the Nanija Bolong and several temporary drainage channels; ponds, low-lying areas, natural depressions, and reservoirs constitute spaces for the temporary concentration or storage of water. These resources can support agricultural and pastoral activities, but their spatial distribution and actual availability must be precisely characterized to guide interventions. Research conducted in other areas of Senegal demonstrates the value of a multi-temporal approach to analyze variations in water surface areas and their relationships with agricultural systems, particularly in the Senegal River valley (Ogilvie et al., 2020; Ogilvie et al., 2025). These results provide a framework for comparison, without assuming that the mechanisms or amplitudes observed in this valley are identical to those of the Nanija Bolong.

Despite methodological advances, mapping surface water resources in small Sahelian watersheds still faces several challenges: the temporary nature of water bodies, the small size of some ponds, turbidity, the presence of aquatic vegetation, the uneven availability of cloud-free images, and the scarcity of hydrometric observations. Furthermore, water surface maps alone are insufficient to establish the feasibility of hydro-agricultural development. They must be considered in conjunction with topographic, pedological, hydrological, environmental, and socio-economic characteristics. In this context, the objective of this article is to analyze the contribution of spatial analysis to the identification and characterization of surface water potential in the Nanija Bolong watershed, with a view to informing hydro-agricultural planning. More specifically, it aims to: (i) characterize the organization of the hydrographic network and storage units; (ii) describe the seasonality and functions of surface resources based on available information; (iii) present the mapping tools used; and (iv) discuss the conditions and limitations of integrating this information into development planning

2. Materials and methods

2.1. Study Area

The Nanija Bolong watershed is located in the Kaffrine region of central Senegal, in a Sudano-Sahelian environment characterized by a relatively short rainy season and a long dry season (Fig.1). The study area covers approximately 3,700 km². The topography is generally flat, but slight variations in altitude, local slopes, valleys, and depressions play a significant role in concentrating runoff and locating wetlands.

The hydrological functioning of the system depends primarily on seasonal rainfall. Rainfall from June to October feeds the drainage network and promotes the filling of ponds and low-lying areas. At the end of the rainy season, runoff decreases and stored water gradually diminishes. This cycle determines the availability of water for recession agriculture, market gardening, and livestock watering.

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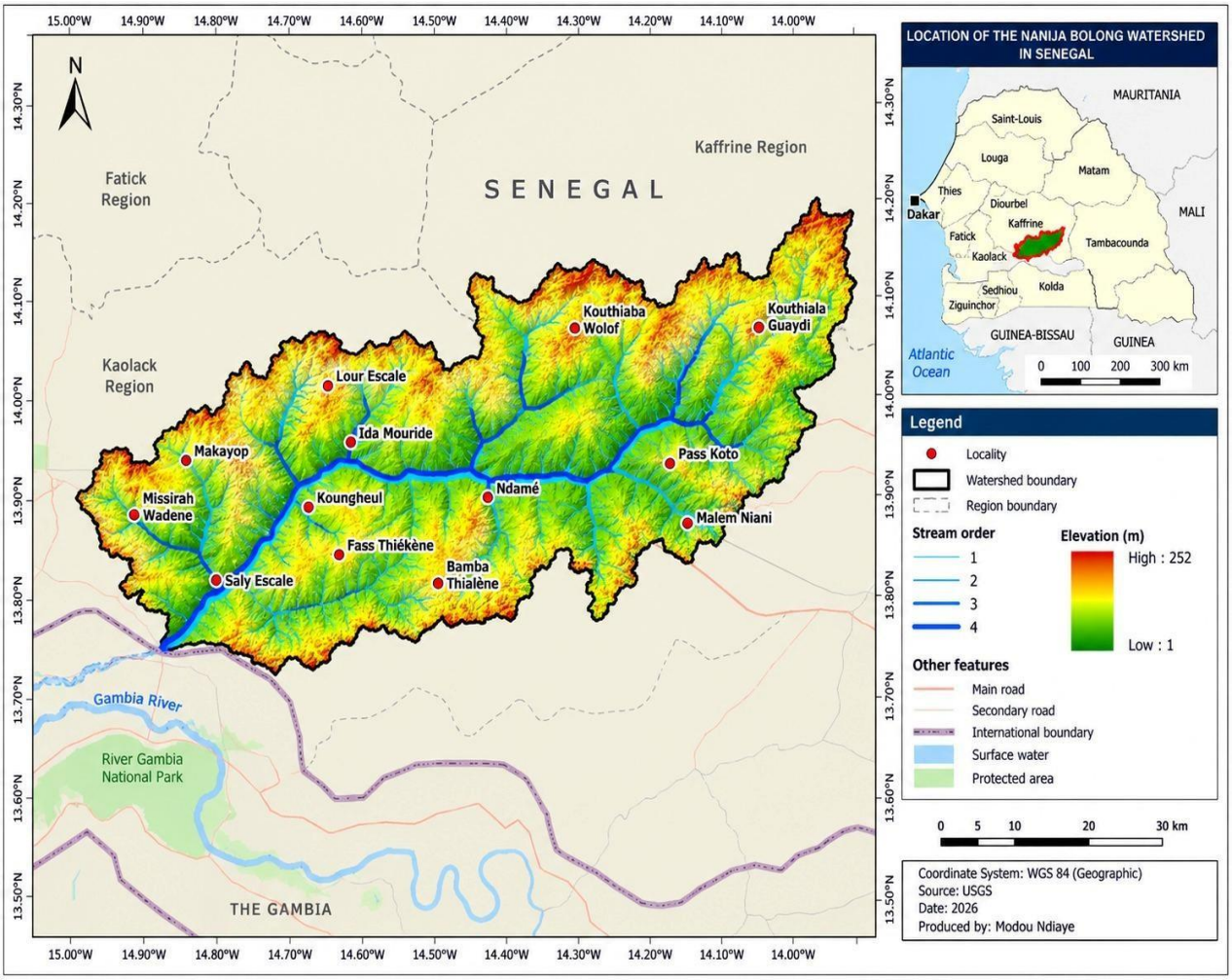


Fig. 1: Location of the Nanija Bolong watershed

Agricultural and pastoral activities structure land use. Water sources and lowlands are of economic and social importance, but their exploitation must be reconciled with maintaining the ecological functions of wetlands, protecting banks, and preventing siltation.

2.2. Data Sources

Surface water resource mapping relies on an integrated approach combining topographic, hydrographic, satellite, and field observation data covering the period 1981–2024. The main datasets used are the 30 m SRTM DEM, 10 m Sentinel-2 imagery, OpenStreetMap hydrographic data , national water resource inventories, and GPS surveys conducted during field campaigns. Processing was performed using ArcGIS Pro with the Spatial Analyst and Hydrology extensions , and supplemented by Google Earth Engine for satellite image analysis (Table 1).

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Table 1: Data used

Source	Features	Contribution to the analysis
SRTM	MNT, 30 m	flow directions and accumulations , slopes , depressions
Sentinel-2 MSI	10 m resolution (bands) visible and close infrared)	Identification of water surfaces , wetlands and humidity indices
OpenStreetMap	Network hydrographic vector	Complement and comparison of the network extract from the MNT
Inventories nationals	Resource data in water	Inventory verification and enrichment
GPS/terrain readings	Localized observations	Object control maps and interpretation functional
Socio- economic surveys	Uses and seasonality declared	Analysis of the local importance of water points

2.3. Network Extraction and Prioritization hydrographic

The hydrographic network is extracted from the SRTM DEM using a series of hydrological processing steps. The first step involves correcting artificial depressions in the digital terrain model using the Fill tool. The flow direction is then calculated, followed by flow accumulation to identify runoff concentration axes. An accumulation threshold is used to define the cells belonging to the network. The streams are then hierarchically ordered according to Strahler stream order and converted into vector features using Stream to Feature . This automated extraction method identifies primary and secondary channels, but it must be compared with existing hydrographic data and field observations. In low-contrast environments, the choice of the accumulation threshold strongly influences the density of the extracted network. Temporary channels may be underrepresented, or conversely, some diffuse runoff features may be interpreted as streams.

2.4. Identification of ponds, shallows and storage areas

Temporary ponds, natural depressions, and low-lying areas are identified by combining several indicators: low elevations, gentle slopes, areas of high runoff accumulation, closed depressions derived from the DEM, moisture indices calculated from Sentinel-2 images, and field observations. Water bodies are verified by photo-interpretation of high-resolution images and by comparison with available hydrological inventories. Alluvial valleys are delineated based on a combined analysis of topography, geomorphology, proximity to the hydrographic network, the presence of hydromorphic soils, and potentially flood-prone areas. Areas characterized by a gentle slope and high runoff accumulation are interpreted as spaces favorable to the temporary storage of runoff and, under certain conditions, to infiltration into surface formations.

2.5. Indicators morpho-hydrological

The quantitative characterization of surface water potential relies on several indicators: total length of the hydrographic network, drainage density, frequency of watercourses, number of ponds identified, area of

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wetlands, area of alluvial valleys, and proportion of temporary storage areas (Table 2). These parameters allow for comparison of spatial units and identification of areas where surface water resources are potentially more accessible.

Table 2: Morpho-hydrological parameters

Indicator	Definition / unit	Interest in planning
Network length	Sum of segment lengths (km)	Appreciate the extension of the drainage network
Drainage density	Network length / area (km/km²)	Compare the drainage structure
Frequency of lessons water	Number of segments relative to the surface area	Identify the concentration of water axes
Number of ponds	Number of objects recorded	Inventory the natural storage points
Area of wetlands	Mapped area (ha or km²)	Identify the environments hydrologically sensitive
Area of the valleys alluvial	Unit surface area alluvial (ha or km²)	Identify the investment sectors in value potential
Storage areas temporary	Surface area of depressions and reservoirs temporary	Identify storage options seasonal

2.6. Integration In the analysis multi-criteria hydro- agricultural

Surface water availability is one of the criteria for the Agricultural Hydro-Potential Index (AHI). In the AHI method adopted in this thesis, it is weighted at 25%, ahead of groundwater (20%) and agro-pedological suitability (20%). The other criteria are slope (10%), erosion risk (10%), land use (5%), distance to water resources (5%), accessibility (3%), and environmental constraints (2% (Table 3)).

Table 3: Weighting of criteria using the AHP method

Criteria	Weight (%)
Resources in surface water	25
Resources in waters underground	20
pedological aptitude	20
Slope	10
Risk erosion	10
Land occupation	5
Distance from resources in water	5
Accessibility	3
Constraints environmental	2
Total	100

The layers are harmonized at 30 m and normalized on a scale of 1 (very unfavorable) to 5 (very favorable). The index is calculated by weighted linear combination: IPHA = $\Sigma(W_i \times X_i)$, where W_i is the criterion weight and X_i its normalized value. The consistency of the AHP matrix is considered acceptable when the CR ratio is less than 0.10. The final index is divided into five classes: P1 (4.0–5.0), P2 (3.2–4.0), P3 (2.4–3.2), P4 (1.6–2.4), and P5 (<1.6). It is important to distinguish between the criterion of surface water availability and the criterion of distance from water resources. The former describes the presence and potential capacity of

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hydrographic features; the latter expresses the spatial proximity of land to watercourses, ponds, and valleys. Proximity does not guarantee the actual availability or quality of water.

3. Results

3.1. Network Organization hydrographic

The basin's hydrographic network is primarily organized around the Nanija Bolong, which constitutes the major drainage axis. The results of this thesis indicate a length of approximately 208 km for this main watercourse. It is fed by several seasonal tributaries and a series of secondary valleys that concentrate runoff during the rainy season (Fig.2).

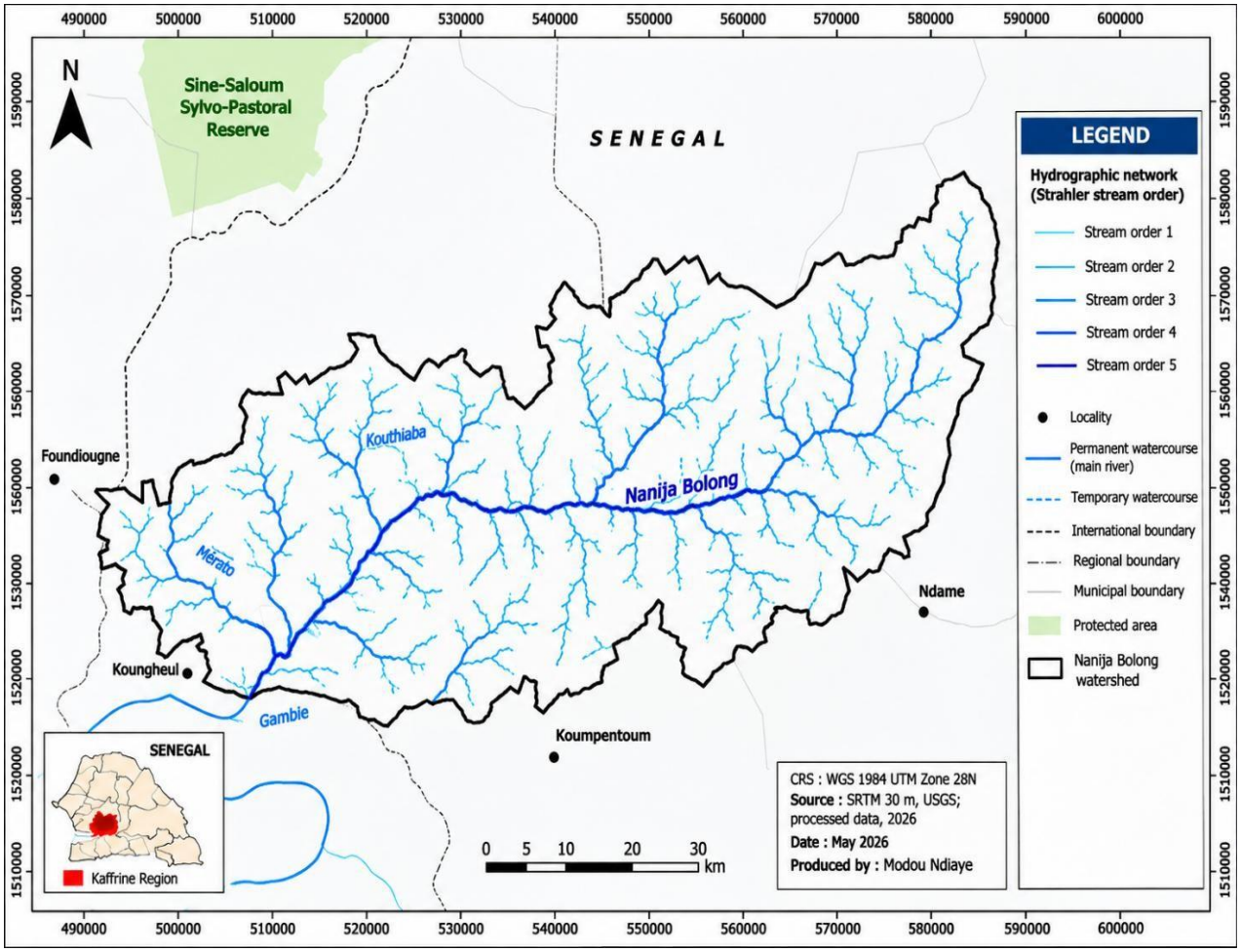


Fig.2: The hydrographic network

The network's operation is highly seasonal. Flows are concentrated primarily between June and October, a period during which rainfall feeds the channels and can cause rapid rises in water levels. During the dry season, flows decrease sharply, and many channels dry up temporarily. Only certain areas retain residual water bodies. This dynamic means that network mapping must distinguish between permanent and temporary watercourses.

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3.2. Ponds, shallows and retentions water

Surface water resources are not limited to the main river and its tributaries. The basin includes temporary pools, shallows, natural depressions, and reservoirs. These features provide temporary storage of runoff, slow its downstream flow, and promote local infiltration. Their role is particularly important during the transition between the rainy and dry seasons (Fig.3).

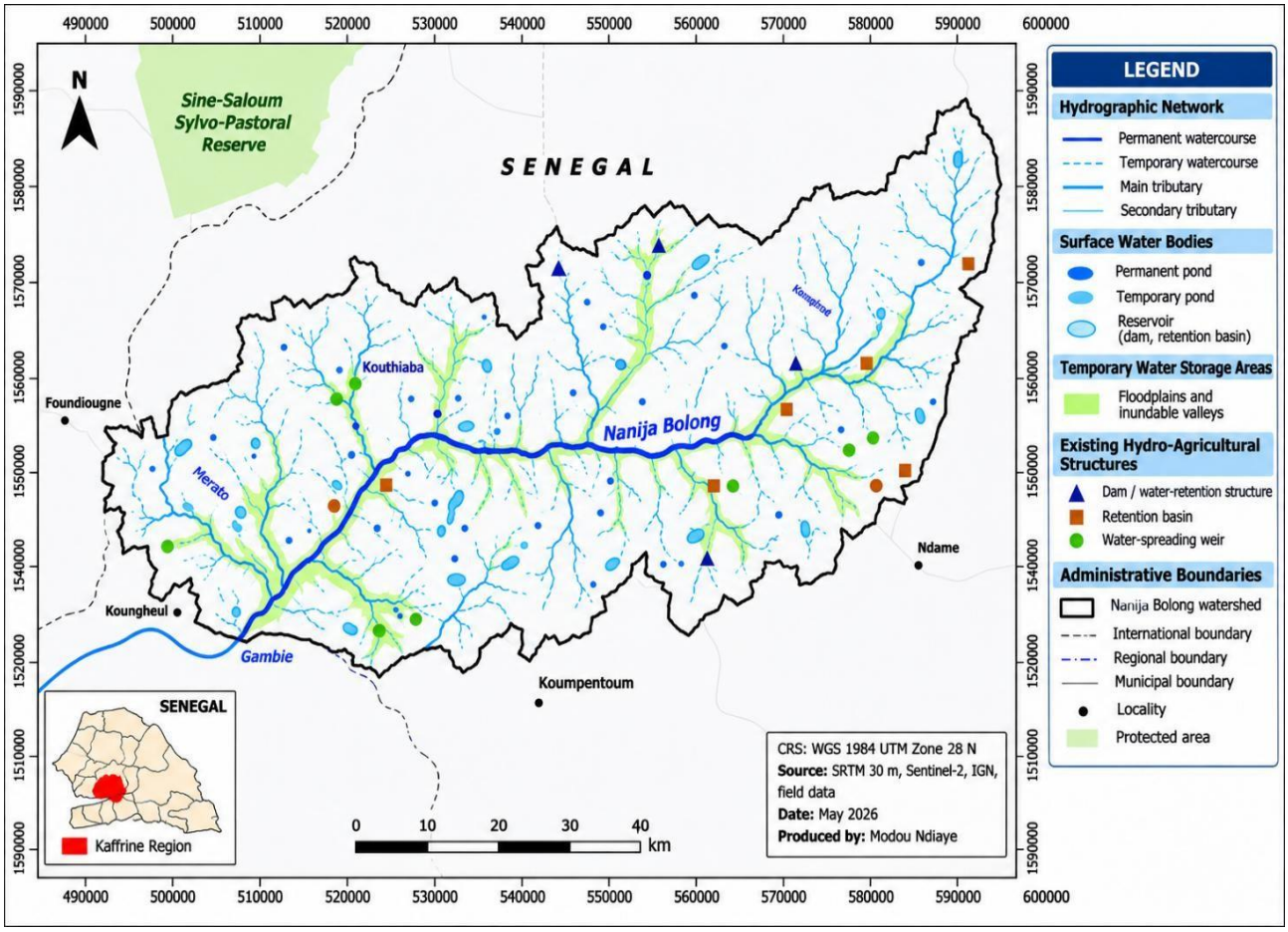


Fig. 3: Inventory of ponds, lowlands and reservoirs

The retention basins of North and South Merato, documented by field observations in August 2026, illustrate the importance of storage infrastructure in local resource mobilization. During the dry season, ponds and reservoirs can support livestock watering, market gardening, and certain domestic uses, depending on the quality and volume of water remaining available. Alluvial valleys and lowlands constitute areas of contact between runoff, hydromorphic soils, and agricultural activities. They can offer opportunities for recession agriculture or small-scale irrigation, but their development must take into account the duration of flooding, soil texture and drainage, susceptibility to siltation, and the ecological functions of wetlands.

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3.3. Seasonality and mobilization constraints

The strong dependence of surface water on rainfall is a key constraint. After rainy periods, inflows can be significant over a relatively short time. Some of the water is stored in ponds, low-lying areas, and depressions, but volumes subsequently decrease due to the combined effects of evaporation, infiltration, and withdrawals. Therefore, the temporary abundance of water during the rainy season does not guarantee that a sufficient resource remains available during the heart of the dry season. Water erosion and sediment transport also contribute to resource degradation. Particles eroded from slopes are transported to valleys and channels; their deposition can promote the silting up of ponds and gradually reduce their depth and storage capacity. Agricultural activity in the immediate vicinity of banks, reduced vegetation cover, and trampling by livestock can exacerbate the fragility of banks and riparian areas.

3.4. Role of surface resources in hydro - agricultural potential

The AHP weighting allocates 25% to surface water resources, reflecting their importance in prioritizing agricultural water potential. This weight must be interpreted in conjunction with other factors: a nearby water resource may not be usable if the soils are unsuitable, if the slope or erosion makes development costly, if access is difficult, or if the area corresponds to an ecologically sensitive wetland.

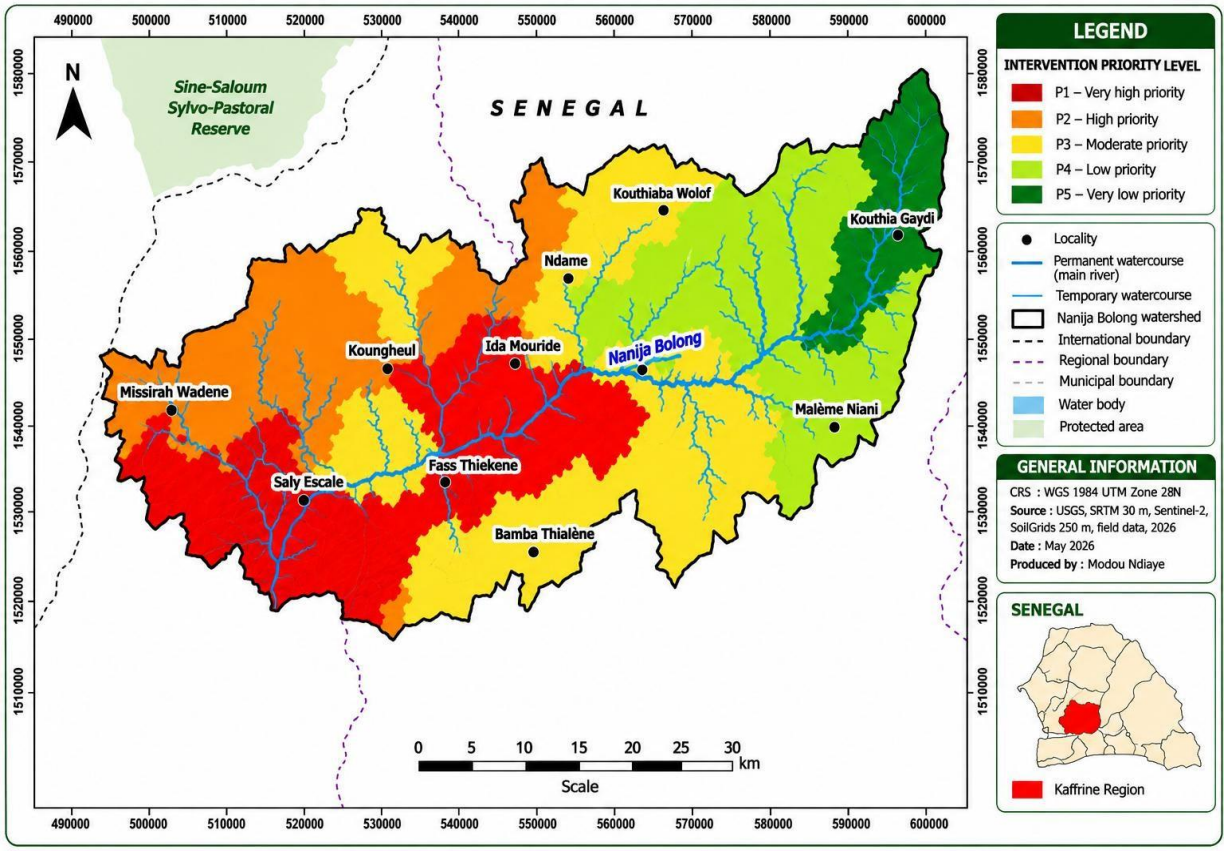


Fig. 4: Overall hydro-agricultural potential (IPHA)

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The overall IPHA results identify 806.85 km² in class P1 (21.81%) and 764.84 km² in class P2 (20.67%), totaling 1,571.69 km² (42.48%) with high or very high potential. Class P3 covers 1,028.13 km² (27.79%), class P4 804.49 km² (21.74%), and class P5 295.69 km² (7.99%). These figures describe the overall hydro-agricultural potential, not just surface water resources (Table 4).

Table 4: Classes of hydro-agricultural potential and development priorities

IPHA Class	Level	Area (km²)	Share (%)
P1	Very pupil	806.85	21.81
P2	Pupil	764.84	20.67
P3	Moderate	1,028.13	27.79
P4	Weak	804.49	21.74
P5	Very weak	295.69	7.99
Total	—	3,700.00	100.00

The spatial distribution of the overall potential highlights favorable sectors in the central and southwestern parts of the basin, particularly around Koungheul , Ida Mouride, and Fass. Thiékène and Saly Escale. This distribution results from the combination of several factors and should not be attributed exclusively to the presence of surface water.

4. Discussion

4.1. Contribution And limitations of remote sensing

The combination of SRTM DEM and Sentinel-2 imagery allows for the documentation of complementary hydrological features. The DEM contributes to the extraction of the drainage network, the delineation of valleys, and the identification of depressions; the multispectral images provide information on the presence of water bodies and the moisture content of vegetation and soils. This complementarity is consistent with the work of Kaptué et al. (2013), which demonstrates the value of satellite observations for characterizing the seasonal distribution of surface water in the Sudanian-Sahelian zone. In northern Senegal, Soti et al. (2009) also showed that indices using the mid-infrared, particularly MNDWI, are relevant for detecting and monitoring temporary ponds. Vector data and field observations remain essential for verifying the interpretation of spectral signatures.

However, temporary ponds may be absent from images acquired during the dry season, while turbidity, aquatic vegetation, shadows, and the small size of water bodies can complicate their detection. Herndon et al. (2020), in the Niger Sahel, show that global surface water products can underestimate small, turbid ponds, which are nevertheless important for local uses. They also emphasize that the performance of spectral indices varies according to site and season, which argues for local calibration and field validation. More recent results obtained in the Ferlo region of Senegal confirm the difficulties in detecting small ponds and the value of combining satellite observations and in situ measurements (study of 22 ponds, published in Frontiers in Water, 2025). Robust mapping of the Nanija Bolong must therefore be based on several dates covering the beginning,

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middle, and end of the rainy season as well as the dry season.

2.2. From the presence of water to availability mobilizable

The concept of surface water potential must be precisely defined. The presence of a channel, pond, or depression is an indicator of water potential, but it does not directly provide information on the stored volume, retention time, regularity of inflows, or water quality. This distinction between mapped extent and actual availability is essential: Herndon et al. (2020) show that satellite detection of small ponds can be incomplete and that simply delineating water bodies is insufficient to characterize the available resource. At the scale of the Senegal River, Ogilvie et al. (2025) combine Earth observations, hydrological modeling, and field data to analyze the variability of flooded areas and their links with agricultural systems. For the Nanija Bolong, the transition from a potential map to a development decision therefore requires hydrometric measurements, bathymetric surveys, seasonal observations and, where relevant, physico-chemical analyses.

The distinction between surface water and groundwater is also essential. Ponds and low-lying areas can contribute to infiltration and local recharge, but this relationship depends on the geology, soil type, and duration of flooding. Papa et al. (2023), in their review of surface water monitoring in Africa, highlight the value of satellite observations for documenting hydrological dynamics, while emphasizing the need to consider them within the broader context of hydrological processes. Therefore, the existence of a temporary storage zone does not, in itself, prove usable aquifer recharge; this hypothesis must be verified by piezometric and hydrogeological data.

4.3. Implications for hydro- agricultural developments

Potential maps can be used to pre-select areas for feasibility studies on small-scale irrigation, pond rehabilitation, lowland development, or the improvement of existing reservoirs. This approach aligns with the findings of Ogilvie et al. (2025) in the Senegal River Valley: variations in flooded areas influence agricultural systems based on flood recession and must be monitored over time to inform water management. In the Nanija Bolong, areas with accessible surface resources, suitable soils, a gentle to moderate slope, and limited susceptibility to erosion can therefore be prioritized, without necessarily being considered technically validated sites from the outset. Areas of high ecological value or those subject to significant flooding must undergo specific assessments before any development work is undertaken.

Planning must also consider competing uses. Water may be used simultaneously for irrigation, livestock farming, domestic purposes, and ecosystem maintenance. Local sharing rules, usage schedules, and maintenance mechanisms are therefore necessary to prevent increased withdrawals from depleting resources during the dry season.

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4.4. Limitations of the study

Detailed quantitative results concerning the total network length, drainage density, number of ponds, cumulative area of the lowlands, and storage volumes are not all available in the extracts of results consulted for the preparation of this manuscript. Therefore, they are not estimated or reconstructed here. Their insertion from the final tables and the thesis geodatabase is essential for a scientific submission.

Furthermore, the 30 m resolution of the DEM does not always allow for the representation of micro-depressions and small channels. The boundaries of water bodies can vary depending on the image acquisition date. Finally, the AHP ranking depends on the weights assigned to the criteria; a sensitivity analysis would allow for measuring the robustness of the classes and identifying areas whose ranking changes significantly depending on the weightings.

5. Conclusion

The spatial analysis of surface water resources in the Nanija Bolong watershed highlights the value of combining topographic data, satellite imagery, hydrographic information, and field observations to characterize the drainage network, ponds, lowlands, alluvial valleys, and temporary storage areas. The Nanija Bolong River, approximately 208 km long, forms the main axis of the network. Its functioning is strongly seasonal, with flows concentrated primarily between June and October and the temporary drying up of many channels during the dry season.

Ponds, lowlands, and reservoirs play a vital role in local water flow regulation and supporting agricultural, pastoral, and domestic activities. However, their storage capacity remains vulnerable to evaporation, water withdrawals, slope erosion, and siltation. Therefore, considering these features in hydro-agricultural planning must combine resource utilization with ecosystem protection.

The integration of surface water resources into the Integrated Water Resources Assessment (IPHA), with a weighting of 25%, allows them to be considered in conjunction with groundwater, soil suitability, slope, erosion, land use, accessibility, and environmental constraints. The overall classes P1 and P2 cover 42.48% of the basin, but this proportion does not constitute an estimate of surface water availability nor a validation of infrastructure sites. The main objective is to supplement the mapping with measurements of volumes, flooding duration, water quality, and seasonal demand, in order to transform the spatial analysis into an operational tool for integrated management.

Data availability

The whole analysis and datasets created are presented in the article.

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Ethics declarations

Clinical trial number: Not applicable.

Competing interests

The authors declare no competing interests.

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Author Contribution:

Modou Ndiaye: Conceptualization, methodology, field investigation, data collection, data curation, formal analysis, visualization, and writing – original draft preparation. **Cheikh Faye**: Conceptualization, methodological supervision, validation, interpretation of results, writing – review and editing, and scientific supervision. Both authors contributed to the critical revision of the manuscript, read and approved the final version, and agreed to be accountable for its content.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work, the author(s) used CHAT-GPT Tool to improve the readability of some parts such as (checking the grammar error, spelling mistakes, long sentences, tenses, and improving the sentences) of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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