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Unveiling climate resilience of Lake Guidimouni: an integrated DPSIR (drivers–pressures–state–impact–response)–GIS framework for water dynamics, vegetation productivity, and human impacts in the Zinder drylands (Niger)

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Lake Guidimouni, a designated Ramsar wetland in Niger's Zinder Region, represents a keystone socio-ecological system whose ecological functions, cultural heritage, and local livelihoods are tightly interwoven. Yet, this emblematic dryland lake is increasingly destabilised by intensifying climatic extremes—prolonged droughts and recurrent floods—and by accelerating anthropogenic pressures. To provide a more rigorous and climate-centred diagnosis of these transformations, we developed and operationalized a spatially explicit, participatory and statistically validated DPSIR–GIS framework integrating object-based image analysis, spatial autocorrelation modelling and NDVI-based carbon proxies. This combined approach enabled the development of a fine-scale vulnerability map of the lake and its periphery, capturing both biophysical and socio-economic dimensions of change. Our findings reveal two converging threats jeopardising ecosystem sustainability: (i) extensive inundation of agricultural lands and (ii) the massive proliferation of the invasive macrophyte *Typha domingensis*. Land-use analysis demonstrates that approximately 77.2 ha of irrigated croplands have transitioned into aquatic grasslands, signalling a structural ecological shift tightly linked to hydrological stress and climate variability. Moreover, 42.5% of irrigated agriculture is now exposed to flooding and exhibits high susceptibility to vegetative invasion. In response to these pressures, we identify targeted, science-based strategies—such as selective mechanical harvesting, hydrological regulation, and adaptive local governance—as priority resilience levers capable of restoring ecological balance and safeguarding ecosystem services. These findings underline the urgent need for integrated natural-resource management in Sahelian drylands. The analysis further integrates convergent stakeholder perceptions collected

through participatory co-production, which were systematically embedded within the DPSIR framework to triangulate and validate spatial and remote-sensing evidence.

KEYWORDS

dryland socio-ecological resilience, ecosystem vulnerability, flooding, Lake Guidimouni, *Typha domingensis*

1 Introduction

African lakes—whether vast like Lake Victoria or more modest like those in the Faguibine system in Mali—play a vital role in ecological regulation, food security, and the livelihoods of surrounding populations (Mutanda and Nhamo, 2024; Abocar et al., 2025). However, these lacustrine ecosystems are increasingly threatened by the effects of climate change. Increased rainfall variability, rising temperatures, reduced water inflows, and accelerated evaporation are profoundly altering their hydrological and ecological functioning (Ali et al., 2024; Taithe, 2014).

In the Great Lakes region, water-level fluctuations disrupt agricultural, fishing, and pastoral activities, while exacerbating social tensions related to resource access (Ogega et al., 2023). In Mali, the Faguibine system, once fed by the Niger River, has experienced chronic drying since the 1970s, undermining the resilience of local communities (Mutanda and Nhamo, 2024).

Despite growing research on African aquatic systems, the resilience of medium-sized Sahelian wetlands—such as Lake Guidimouni—remains insufficiently examined through integrated climate-centred frameworks. Although African lakes and Sahelian wetlands have been studied (Beadle, 1981; Adekola and Mitchella, 2011; Lemoalle et al., 2014), existing work on Lake Guidimouni remains fragmented and sectoral (Souley and Salifou, 2017; Karimou et al., 2015). Previous studies emphasize hydrology, biodiversity, or agricultural use (Tulbure et al., 2007), but none provide a systemic articulation of climate drivers, ecological pressures, ecosystem states, livelihood impacts, and institutional responses.

This lack of integration has important consequences. Interventions such as Typha removal or land-use zoning (Mairie de Guidimouni, 2022) are assessed in isolation, rarely accounting for the feedbacks between climate variability, ecological change, and local adaptive capacity (Bansal et al., 2019; Lishawa et al., 2017). Spatially explicit analyses are scarce (Obubu et al., 2022). Consequently, Lake Guidimouni remains absent from robust resilience frameworks increasingly applied to other Sahelian wetlands (Benzina et al., 2024).

Addressing this gap, our study introduces a DPSIR–GIS approach specifically adapted to climate resilience analysis. This framework enables the identification of climate-related drivers, mapping of vulnerability hotspots, and recognition of resilience levers grounded in both biophysical evidence and local perceptions.

The overarching objective of this research is to identify an integrated climate-resilience assessment system for Lake Guidimouni by explicitly linking climatic drivers, ecological pressures, ecosystem states, socio-economic impacts, and adaptive responses within a DPSIR–GIS analytical framework. This objective reflects the diagnostic and analytical nature of the study and ensures full coherence with its climate-resilience focus.

2 DPSIR conceptual framework: a systemic approach to environmental analysis

The DPSIR (Drivers–Pressures–State–Impact–Response) framework provides a widely recognised structure for diagnosing environmental change, especially in complex socio-ecological systems subject to multiple stressors (Figure 1). In the context of Lake Guidimouni, we adopt an enhanced, climate-centred and participatory DPSIR approach that enables a more rigorous interpretation of how climatic variability interacts with ecological processes, land-use dynamics, and local livelihoods. This adaptation ensures coherence with the overarching focus of the study on climate resilience.

Drivers refer to the underlying climatic and anthropogenic forces that initiate system change. In dryland wetlands such as Lake Guidimouni, the dominant drivers include increasing rainfall irregularity, intensifying flood–drought cycles, rising temperatures, and shifts in local land-use strategies driven by demographic and economic pressures (Smeets and Weterings, 1999). These drivers establish the baseline conditions under which environmental transformations occur.

Pressures represent the direct mechanisms through which drivers alter ecosystem functioning (Niemeijer and de Groot, 2008). For Guidimouni, these include hydrological stress (flooding and seasonal desiccation), accelerated sedimentation, and the proliferation of *Typha domingensis*, whose expansion is tightly linked to hydrological instability and climate-driven nutrient fluxes. By integrating participatory data and spatial layers, we translate these pressures into measurable indicators that can be mapped and compared across the landscape.

State describes the condition of the ecosystem and reflects the cumulative effects of pressures (Smeets and Weterings, 1999). The state of Lake Guidimouni is characterised by a rapid transition from open water to Typha-dominated marshlands, reduction of irrigable areas, and fragmentation of aquatic habitats, confirming a shift toward a more vulnerable ecological configuration. These state changes are captured through high-resolution land-use classification, field observations and spatial analysis.

Impacts correspond to the consequences of these state changes for ecological processes, agricultural productivity, biodiversity and human livelihoods (Svarstad et al., 2008). In Guidimouni, impacts include reduced water availability for irrigation, loss of arable land, increased labour requirements for farmers, diminished habitat quality, and heightened exposure of local communities to climate

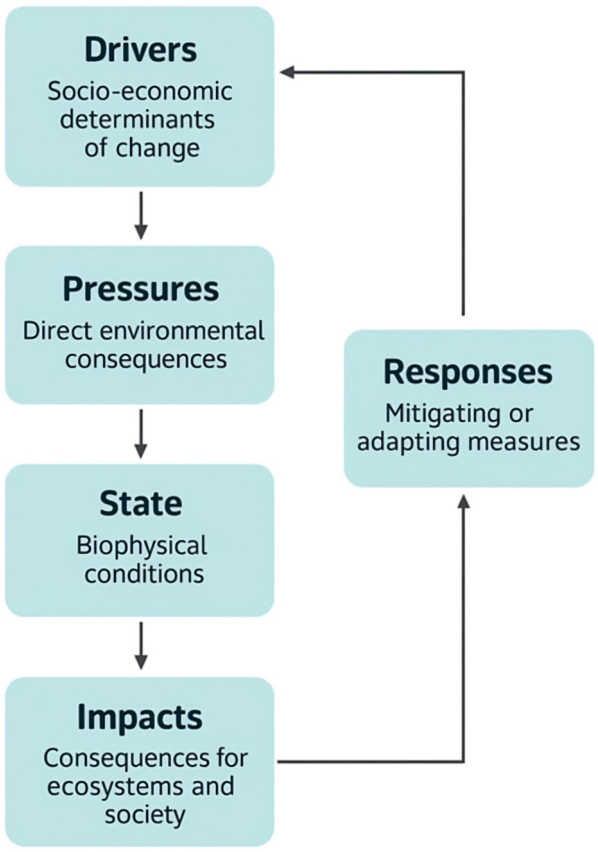


FIGURE 1
Climate-centred DPSIR–GIS conceptual framework for diagnosing socio-ecological vulnerability and resilience pathways in Lake Guidimouni (Niger). Conceptual representation of the integrated DPSIR (Drivers–Pressures–State–Impacts–Responses) framework developed and operationalised in this study to analyse climate-driven socio-ecological transformations in Lake Guidimouni. Climatic and anthropogenic Drivers (e.g., rainfall variability, flood–drought alternation, rising temperatures, land-use intensification) generate multiple Pressures, including recurrent inundation, sediment redistribution and the invasive proliferation of *Typha domingensis*. These pressures alter the ecological State of the system, manifested by hydrological instability, conversion of irrigated cropland into aquatic grasslands, loss of open-water habitats and landscape homogenisation. Resulting Impacts cascade across ecological and socio-economic domains, affecting agricultural productivity, biodiversity, water availability, livelihoods and exposure to climate-related risks. Responses encompass locally grounded and science-based resilience levers—such as selective mechanical removal of *Typha domingensis*, hydrological regulation, adaptive land-use planning and participatory governance—designed to mitigate impacts and restore system functionality. Arrows indicate causal linkages and feedback loops between DPSIR components, highlighting the non-linear and dynamic nature of the lake's socio-ecological system. The framework explicitly integrates spatial evidence derived from multi-temporal satellite imagery (2013–2024), GIS-based analyses and convergent stakeholder perceptions, providing a diagnostic scaffold for identifying vulnerability hotspots and prioritising actionable climate-resilience strategies in Sahelian dryland wetlands.

extremes. This integrated reading links biophysical degradation with socio-economic vulnerability.

Responses encompass the strategies, policies, and local practices implemented to mitigate negative impacts or reinforce resilience (OECD, 2014). The responses observed or recommended for Guidimouni include selective mechanical removal of *Typha domingensis*, adaptive land-use planning, improved hydrological management, and community-based governance mechanisms. By situating these actions within the DPSIR logic, we identify leverage points where interventions can achieve the greatest ecological and socio-economic benefits.

Importantly, our study employs a reflexive and adaptive interpretation of DPSIR, acknowledging that responses can generate new pressures (e.g., overharvesting, governance gaps), and that feedback loops between drivers, pressures and state changes may reinforce or accelerate system vulnerabilities. This dynamic reading aligns with recent calls to evolve DPSIR into more temporal, non-linear analytical forms that better capture the complexities of climate-sensitive ecosystems (Hocherman et al., 2022; Obubu et al., 2022).

By integrating field perceptions, geospatial datasets, and conceptual systems analysis, the DPSIR framework becomes a powerful diagnostic tool for identifying vulnerability hotspots, interpreting ecological transitions, and supporting targeted climate-resilience strategies in Lake Guidimouni and similar Sahelian wetlands.

3 Methodology

3.1 Study area

Lake Guidimouni is located in the Zinder Region of southeastern Niger and constitutes one of the most important semi-permanent wetlands in the area. The lake supports multiple livelihood activities including irrigated agriculture, fishing, pastoralism, and traditional cultural practices. Lake Guidimouni is characterised by high climate sensitivity, ecological significance, and socio-economic importance within a Sahelian dryland context. The regional climate is Sahelian, marked by strong interannual rainfall variability, recurrent droughts, and episodic flooding events, all of which exert direct influence on hydrological processes and land-use dynamics. Vegetation surrounding the lake includes key species such as *Phoenix dactylifera*, *Acacia nilotica*, *Faidherbia albida*, and *Balanites aegyptiaca*, which are central to agro-silvo-pastoral livelihoods (Ramsar Convention Secretariat, 2018).

This ecological assemblage has become increasingly destabilised by altered hydrological regimes—characterised by recurrent inundation and prolonged waterlogging—which modify nutrient cycling and create favourable conditions for the rapid proliferation of the invasive macrophyte *Typha domingensis*. The expansion of *Typha* is thus driven by coupled hydrological and biogeochemical processes that reinforce vegetation dominance and suppress open-water and agricultural habitats. To enhance spatial precision and analytical clarity, the location map (Figure 2) has been refined to centre explicitly on Lake Guidimouni and its immediate socio-ecological surroundings.

3.2 Integrating multi-source data and participatory DPSIR co-construction

To ensure methodological coherence and analytical robustness, primary, secondary, spatial, and participatory data were jointly

mobilised within a unified DPSIR operational framework. Primary data were collected through semi-structured interviews and collective working sessions involving farmers, fishers, pastoralists, traditional leaders, women's groups, municipal authorities, and local environmental NGOs. At least five stakeholder representatives, formally designated by their respective associations, actively participated in the co-construction workshop. The data collection relied on a semi-structured interview guide designed for participatory co-production.

The participatory process focused on identifying convergent perceptions rather than isolated individual narratives. Information collected addressed shared perceptions of climate variability, hydrological changes, vegetation dynamics, land-use pressures, vulnerability thresholds, and locally proposed adaptation strategies. These qualitative inputs were systematically structured according to the Drivers, Pressures, State, Impact, and Response dimensions of the DPSIR framework and integrated into the analytical workflow.

Complementary GPS-based field surveys were conducted to record geolocated wetland boundaries, Typha domingensis stands, irrigated plots, and flood-affected zones, providing field-validated spatial references for remote-sensing interpretation.

Secondary data were sourced from municipal development plans, environmental bulletins, hydrological reports, and institutional documents from national and regional agencies. These sources were explicitly linked to their analytical use in the Results section to ensure transparency and traceability.

Participatory co-production was operationalised through iterative confrontation of spatial results with local knowledge during collaborative workshops. This triangulation enabled validation of remote-sensing outputs, refinement of vulnerability thresholds, and identification of context-specific resilience pathways grounded in lived socio-ecological realities (Karimou et al., 2018).

3.3 Analytical workflow and operationalisation of the DPSIR framework

Climatic drivers—including rainfall variability, intensifying flood–drought cycles, and rising temperatures—were identified as the primary forces shaping ecological and socio-economic transformations. These drivers were derived through the combined analysis of stakeholder perceptions, institutional documentation, and spatial observations, ensuring alignment between local experience and biophysical evidence. Climatic drivers are explicitly identified as the dominant forces structuring both ecological dynamics and socio-economic transformations within the Lake Guidimouni system. These drivers manifest through a set of interconnected pressures, notably recurrent inundation, enhanced sedimentation, and the rapid invasive expansion of *Typha domingensis*. Typha density was quantified through the combined analysis of field observations and satellite imagery, allowing the classification of vulnerability into three ecologically meaningful thresholds (<25%, 25%–75%, >75%). These thresholds reflect observed tipping points beyond which Typha dominance substantially alters hydrological functioning, land accessibility, and ecosystem services. The ecological state of the system was assessed through land-cover transitions, particularly the contraction of open water and the conversion of irrigated cropland into marshland. These state changes were then linked to their impacts on agricultural productivity, habitat quality, water availability, and local livelihoods. Biophysical degradation and socio-economic vulnerability are analysed as tightly coupled processes, allowing ecological change to be interpreted in direct relation to livelihood exposure, adaptive capacity, and governance constraints. Response options are derived from both observed community practices and scientifically grounded management strategies, including selective mechanical removal of *Typha domingensis*, improved hydrological regulation, and adaptive local governance mechanisms. This integrated analytical workflow ensures a rigorous and transparent operationalisation of the DPSIR framework, enabling coherent linkage between drivers, impacts, and actionable resilience pathways.

3.4 Uncertainty analysis, feedback loops, and adaptive refinement

Given the non-linear and dynamic nature of socio-ecological systems, uncertainty was explicitly addressed through sensitivity analyses and participatory calibration. Socio-ecological systems are inherently complex, non-linear, and characterised by high uncertainty. The uncertainty assessment has been strengthened to explicitly demonstrate how the methodological framework accounts for instability in indicators, weighting choices, and future climatic trajectories. To address uncertainty, we conducted a series of sensitivity analyses in which indicator weights and classification thresholds were systematically varied to test the stability and robustness of vulnerability outputs. This step ensures that the vulnerability maps are not artefacts of arbitrary parameter selection but reflect structural patterns in the ecosystem.

Building on this, we generated scenario ensembles representing multiple plausible futures, including wetter rainfall regimes, enhanced irrigation development, and intensified hydrological stress. These contrasting scenarios were compared to assess spatial divergences in ecosystem trajectories and to evaluate the resilience of land-use systems under changing climatic and anthropogenic pressures. This scenario-based refinement strengthens the causal linkage between climate variability and spatial patterns of vulnerability, enabling a more robust interpretation of how alternative climatic trajectories may reshape ecosystem dynamics and exposure to risk. Stakeholder participation played a central role in refining model structure and outputs. Preliminary vulnerability maps were presented to farmers, fishers, pastoralists, and local authorities. Their feedback was incorporated through an iterative process, allowing the adjustment of indicator relevance, weighting choices, or threshold definitions based on grounded local knowledge. This participatory calibration strengthened the validity of the DPSIR operationalisation and enhanced its contextual relevance.

Furthermore, feedback loops were incorporated to account for dynamic interactions between DPSIR components, recognising that responses—such as Typha removal or new irrigation infrastructure—may themselves generate new pressures or reshape drivers. To reflect this, relational links within the DPSIR structure were revisited *post hoc*, and institutional modifiers such as policy inertia, governance gaps, and resource-use conflicts were explicitly integrated into the analytical model, aligning with

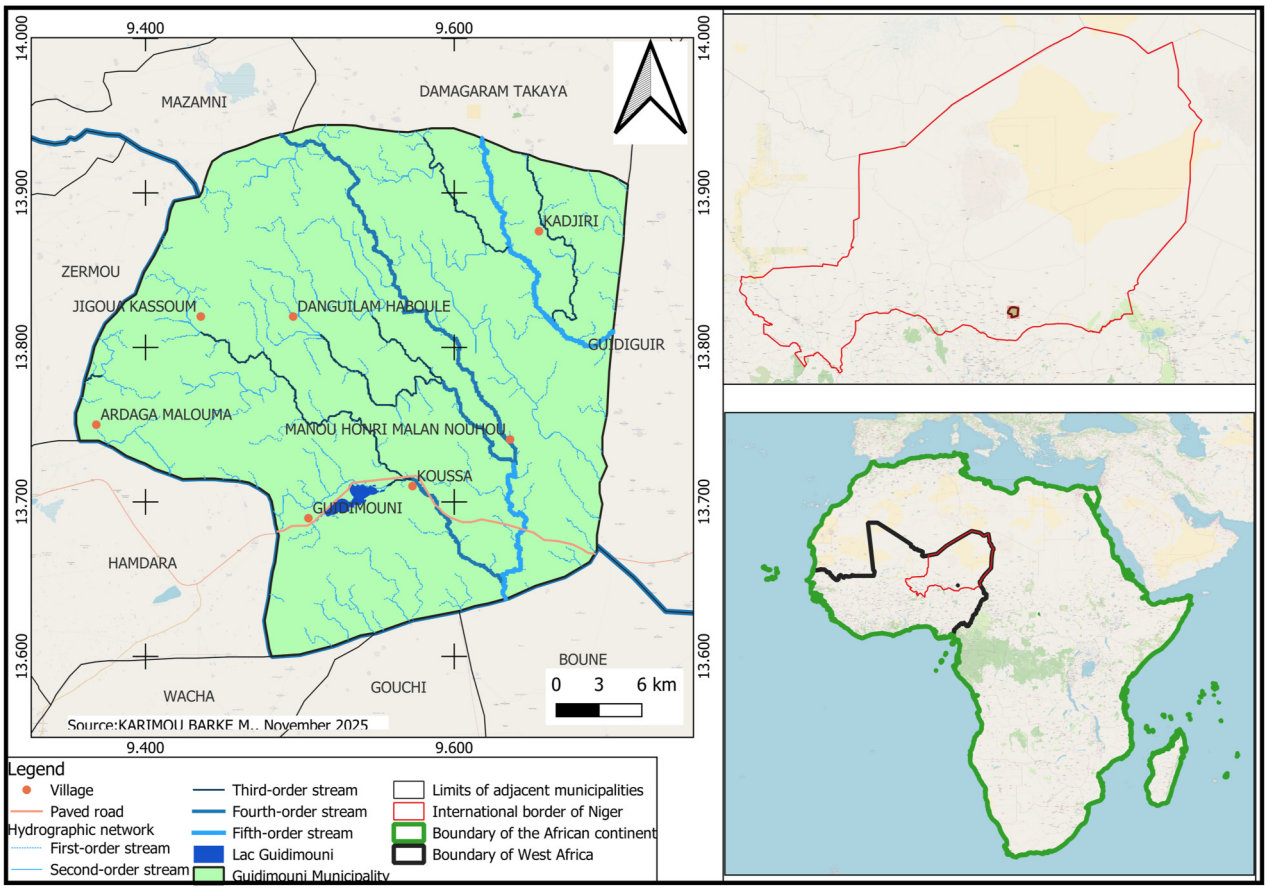


FIGURE 2
Geographical setting and socio-ecological context of Lake Guidimouni within the Sahelian drylands of south-eastern Niger. Location map of Lake Guidimouni illustrating its geographical position within the Zinder Region of south-eastern Niger and its embedding within a climate-sensitive Sahelian dryland landscape. The figure situates the lake at multiple spatial scales, highlighting its regional context, hydro-geomorphological setting, and proximity to surrounding land-use units that sustain irrigated agriculture, pastoralism, fishing activities and settlement development. The map delineates the lake perimeter and its immediate socio-ecological surroundings, which constitute the core spatial domain analysed in this study. This spatial framing is essential for interpreting climate-driven hydrological variability, land-use dynamics and ecosystem vulnerability assessed through the DPSIR–GIS framework. By explicitly locating Lake Guidimouni within a zone characterised by high interannual rainfall variability, recurrent flood–drought alternation and strong anthropogenic pressure, the figure provides the geographical foundation for understanding the observed proliferation of *Typha domingensis*, the conversion of irrigated croplands into aquatic grasslands, and the cascading socio-ecological impacts documented between 2013 and 2024. The map therefore serves not merely as contextual information, but as a spatial reference underpinning all subsequent remote-sensing analyses, vulnerability mapping and resilience diagnostics developed in the manuscript.

approaches advocated by Carnohan et al. (2023). Through these combined steps, the methodology remains open, reflexive, and capable of continuous improvement. Table 1 synthesises the discussion questions used to explore each DPSIR dimension.

3.5 Multi-scale spatial analysis (GIS & remote sensing)

Geospatial analysis was mobilised to complement local perceptions with objective, spatially explicit evidence. The 2013 SPOT image (2.5 m resolution) was acquired during earlier doctoral research and reused as a validated historical reference, while the 2024 Sentinel-2 image (10 m resolution) was selected due to budgetary and data-availability constraints. We also clarify that potential resolution-related biases were mitigated through object-based image analysis, field validation, and triangulation with participatory and GIS-based data. Satellite imagery from 2013 to 2024 was processed using an object-oriented classification approach, following established procedures such as those described by Karimou et al. (2015). The methodological description has been expanded to better demonstrate how object-based image analysis improves the detection of ecological transitions in dynamic wetland environments. Image segmentation and classification were carried out using eCognition software, while QGIS was employed for map layout, spatial overlay, and final cartographic design.

This multi-scale GIS approach enabled detailed visualisation of spatial pressures affecting the ecosystem, including hydrological fluctuations, Typha proliferation, and land-use conversion. It also facilitated the identification of ecological vulnerability zones and the temporal tracking of land-cover changes between 2013 and 2024. By linking these spatial patterns to DPSIR dimensions, the GIS analysis provided a robust foundation for territorial planning and informed decision-making.

TABLE 1 Environmental analysis of the Lake using the DPSIR framework.

DPSIR component	Analytical objective
Driving forces	Identify socio-economic and cultural dynamics behind observed transformations
Pressures	Examine direct environmental disturbances (pollution, overuse, artificialization)
State	Assess the current ecological condition of the lake: water quality, vegetation, fauna
Impacts	Analyze effects on human health, biodiversity, and livelihoods
Responses	Co-develop technical, institutional, and policy solutions for sustainable management

3.6 Classification accuracy assessment

To ensure the robustness of land-cover classification results, an accuracy assessment was conducted using independent validation samples. A total of 210 ground-truth and high-resolution Google Earth reference points were used, with 70% allocated to training and 30% to validation (Table 2).

A confusion matrix was generated to compute: (i) Overall Accuracy (OA), (ii) Producer's Accuracy (PA), (iii) User's Accuracy (UA), (iv) Kappa coefficient (κ).

The confusion matrix was calculated for the 2024 Sentinel-2 classification, using independent validation samples derived from field observations and high-resolution Google Earth imagery (Table 3). The 2013 SPOT classification had been previously validated in regional semi-arid land-cover studies (Karimou et al., 2018) and was therefore used as a historical reference layer for the change-detection analysis.

The overall classification accuracy reached 87.6%, with a Kappa coefficient of 0.84, indicating strong agreement beyond chance. Class-level accuracies exceeded 80% for major land-cover types, including water bodies, irrigated agriculture, rainfed agriculture, and Typha-dominated grasslands.

These results confirm the reliability of change-detection outputs between 2013 and 2024.

TABLE 2 Distribution of reference samples by land use class (N = 210).

Class	Samples
Water body	35
Aquatic grassland (Typha)	40
Irrigated agriculture	45
Rainfed agriculture	50
Settlement	20
Sandy area	20

3.7 Annual rate of spatial expansion

To quantify the pace of land-cover transitions, the annual rate of spatial expansion was calculated using the formulation proposed by Oloukoi et al. (2006). The method models the average annual growth rate (T) of a given land-cover class between two dates (S_1 for 2013 and S_2 for 2024) according to the equation:

$$T = \frac{\ln S_2 - \ln S_1}{t \ln e} \times 100$$

where t is the number of years between the two observations and $e \approx 2.718$ is the base of the natural logarithm. This formulation has been retained due to its suitability for capturing exponential ecological transitions such as the rapid spread of *Typha domingensis* or the expansion of inundated zones.

3.8 NDVI-based vegetation productivity analysis

To operationalise the vegetation productivity and carbon-related dimension within the DPSIR analytical framework, NDVI was derived from Sentinel-2 imagery and used as a relative proxy for aboveground vegetation dynamics rather than converted into absolute biomass values. Specifically, we used the maximum seasonal NDVI (NDVImax) for each year, representing peak photosynthetic activity during the growing season. This metric has been widely applied in dryland productivity studies and is particularly suitable for Sahelian ecosystems characterised by strong seasonality and short vegetation cycles (Tucker et al., 1985; Prince, 1991).

Accordingly, NDVI-derived spatial patterns were interpreted comparatively to assess vegetation productivity changes between 2013 and 2024 rather than to estimate absolute aboveground biomass or carbon stocks. This approach avoids uncertainties associated with site-specific biomass calibration and provides a robust basis for analysing spatial ecological trajectories (Compton et al., 1985).

Spatial NDVImax maps were generated for both 2013 and 2024 to identify areas of increasing vegetation dominance—particularly associated with *Typha domingensis* expansion—and zones of declining productivity linked to shrubland loss and hydrological instability. These NDVI-derived productivity patterns were subsequently integrated into the DPSIR framework as ecological indicators supporting interpretation of land degradation dynamics and vulnerability patterns across the study area (Bastin et al., 2012).

We therefore explicitly frame these estimates as relative aboveground productivity proxies rather than absolute ecosystem carbon stocks, with the objective of capturing spatial change trajectories rather than producing definitive carbon accounting estimates.

This relative approach is consistent with recent dryland remote sensing studies emphasising NDVI-based productivity gradients over absolute biomass estimation (Bastin et al., 2012; Prince, 1991).

TABLE 3 Confusion matrix of land cover classification results.

Reference/classified	Water	Typha	Irrigated	Rainfed	Settlement	Sand
Water	32	2	0	0	0	1
Typha	3	34	1	1	0	1
Irrigated	0	2	39	3	0	1
Rainfed	0	1	3	44	1	1
Settlement	0	0	0	2	17	1
Sand	1	0	1	1	1	16

3.9 Mapping Typha ulnerability

The density of the invasive species *Typha domingensis* was assessed using a combination of field-based visual observations and interpretation of satellite imagery. The methodological explanation has been expanded to clarify the rationale behind the classification thresholds and the integration of field and remote-sensing data. Three vulnerability levels were established—low, medium, and high—based on density thresholds of <25%, 25%–75%, and >75% respectively (Table 4). These thresholds were selected because they align with ecological tipping points observed during ground surveys, whereby *Typha* dominance above 75% typically leads to substantial declines in open water and agricultural land accessibility.

Density estimates were therefore derived through an iterative process combining field observations with high-resolution visual interpretation, ensuring that the resulting vulnerability map reflects real biophysical conditions rather than purely modelled outputs. This combined approach strengthens the ecological validity of the Typha vulnerability assessment and situates it firmly within the DPSIR analytical structure.

3.10 Methodological innovation beyond conventional DPSIR

While DPSIR has been widely applied as a conceptual diagnostic tool, its operationalization often remains descriptive and linear. In contrast, the present study introduces four methodological advancements.

First, DPSIR components are spatially operationalised through object-based image analysis (OBIA), enabling the translation of Drivers, Pressures, and State variables into georeferenced indicators derived from multi-temporal satellite imagery. This transforms DPSIR from a conceptual framework into a spatially explicit modelling tool.

Second, stakeholder knowledge is structurally embedded within the analytical workflow through a mixed-method integration process combining semi-structured interviews, participatory workshops, and spatial triangulation. Interview responses were coded into DPSIR variables and quantified as perception frequencies (e.g., irrigation decline, wetland encroachment, flooding trends). These were systematically compared with remotely sensed indicators (NDVI trends, land-use transitions), enabling triangulation between stakeholder knowledge and satellite-derived evidence (see Supplementary Table SA1).

Third, feedback loops were identified through iterative integration of spatial trends and stakeholder narratives within the DPSIR framework. Rather than formal parameterization, loops were interpreted as reinforcing system dynamics (e.g., irrigation decline → wetland contraction → reduced livelihoods → intensified land-use pressure), confirmed through both temporal satellite analysis and stakeholder consensus.

Fourth, we introduce vulnerability thresholds (e.g., Typha density tipping points) grounded in ecological field validation, thereby linking conceptual categories to measurable resilience tipping points.

These innovations position the DPSIR–GIS framework as a hybrid spatial-diagnostic system rather than a purely conceptual scaffold.

These methodological innovations are subsequently validated through spatial autocorrelation analysis (Section 4.5) and carbon proxy mapping (Section 3.8), ensuring coherence between conceptual modelling and empirical verification.

4 Results and discussion

Stakeholder perceptions consistently reported increased flooding frequency, rising groundwater levels, and accelerated expansion of Typha domingensis over the last decade. These convergent observations corroborated satellite-derived change-detection results and were integrated into the DPSIR 'Pressures' dimension by spatially matching them with zones exhibiting the highest rates of hydrological instability and land-use conversion.

NDVI-derived biomass patterns further supported these findings by revealing spatially consistent declines in vegetation productivity in areas affected by prolonged inundation and invasive macrophyte expansion, reinforcing DPSIR-based interpretations of ecosystem degradation trajectories.

4.1 Environmental analysis of Lake Guidimouni based on the DPSIR framework

4.1.1 Driving forces

Across all interviewed stakeholder groups (farmers, fishers, pastoralists, and local authorities), climate variability—particularly increasingly erratic rainfall and recurrent flood–drought alternation—was unanimously perceived as the dominant driver reshaping the lake system.

TABLE 4 Estimated Typha density by vulnerability level.

Vulnerability level	Estimated Typha density
Low	<25%
Moderate	25%–75%
High	>75%

At Lake Guidimouni, the driving forces are the deep-rooted natural and socio-economic processes that precondition environmental change (Nelson et al., 2007; Maxim et al., 2009). On the environmental side, climate variability and change manifest through erratic rainfall regimes, rising groundwater levels, intensification of gully erosion and expansion of resurgence zones—processes now well-documented across Sahelian wetlands (Iradukunda et al., 2020). These climatic fluctuations increasingly shape hydrological behaviour at Guidimouni, creating conditions favourable to prolonged inundation and the expansion of waterlogged areas. On the human side, the intensification of irrigated agriculture, pursuit of short-term economic profitability, proliferation of actors competing for water, and the outward growth of the Guidimouni settlement create a powerful cocktail of pressures. Together, these forces constitute a structural backdrop of risk against which the lake's ecological integrity is continually negotiated (Figure 3).

4.1.2 Pressures

Stakeholders consistently identified recurrent flooding of cropland and rapid colonisation by *Typha domingensis* as the most tangible pressures affecting their livelihoods, a perception that guided the prioritisation of spatial indicators analysed below.

Pressures are the proximate expressions of those deeper forces: proliferation of aquatic macrophytes, recurrent flooding of cropland, submersion of tree stands, expansion of the lake's surface area, agrochemical inputs, solid-waste dumping, demographic surge, water-use conflicts, sedimentation and erosion. Our DPSIR analysis highlights two emblematic pressures—dense colonisation by *Typha domingensis* and *Phragmites australis*, and recurrent flooding linked to rising groundwater and intensified resurgences under extreme climate variability (Tulbure et al., 2007; Obubu et al., 2022). Both pressures show strong spatial overlap with zones where hydrological instability has increased most sharply over the last decade, indicating that climatic drivers amplify the ecological expression of these pressures. These pressures are altering the lake's physical, chemical, and biological regimes.

Remote-sensing change detection quantifies these shifts. Between 2013 and 2024 the lake's surface expanded at an average +5.03% per year (see Figure 4 and Table 5), culminating in two permanent water bodies of 83.6 ha and 131.0 ha respectively (total 214.6 ha in 2024). This sustained expansion is consistent with stakeholder testimonies describing increasingly frequent flood pulses and rising groundwater tables. A new monodominant aquatic grassland, dominated by *Typha domingensis* on the western shore, has emerged from the conversion of 77.2 ha of former irrigated farmland. Conversely, shrubland vanished completely by 2024, probably through combined anthropogenic and climatic stress—representing a significant loss of biodiversity and regulating ecosystem services.

Settlements show moderate but steady growth (+1.19%/year), mainly on dune ridges west and south of the lake, forming a peripheral belt at the interface of natural and anthropogenic systems. Rainfed agriculture declined from 90% of land cover in 2013 to 81.3% in 2024 (−557 ha), signalling soil fertility loss, land abandonment or conversion to desert/urban uses. Irrigated agriculture along the lakeshore shrank from 215.6 ha to 104.3 ha, reflecting encroachment by aquatic plants and mounting competition for water. Meanwhile, wetland/oasis units expanded by 39 ha in endorheic depressions, linked to rising groundwater. While such micro-oases can bolster biodiversity and food security, they also raise the spectre of use conflicts without adaptive management (Folke, 2006; Wetlands International, CARE Nederland, IWMI, and International Alert, 2020). Stakeholder perceptions consistently reported increased flooding frequency, rising groundwater levels, and accelerated expansion of *Typha domingensis* over the last decade. These convergent observations corroborated satellite-derived change-detection results and were integrated into the DPSIR 'Pressures' dimension by spatially matching them with zones exhibiting the highest rates of hydrological instability and land-use conversion (Osman et al., 2025).

However, several limitations persist, including potential perception biases linked to power asymmetries among influential user groups and constraints associated with the different spatial resolutions of the 2013 and 2024 satellite images; however, these biases were mitigated through systematic triangulation with remote-sensing and spatial data, limiting their influence on final interpretations. Yet the participatory process also exposed the risk of bias from power asymmetries or competing interests among user groups (Bruno, 2023), while remote-sensing data remain constrained by temporal and spatial resolution.

4.1.3 States

According to local stakeholders, the current state of the lake is increasingly characterised by permanent waterlogging, loss of open water, and declining agricultural accessibility—perceptions that align with the observed land-cover transitions toward Typha-dominated marshlands. The state dimension captures the lake's current condition under these pressures: elevated water levels, over-population of crocodiles, infestation by aquatic plants, contamination of farming zones, and massive sand deposition from aeolian and fluvial erosion (Anabi and Chaibou, 2024). These state indicators collectively describe a system gradually shifting toward a more hydrologically unstable and ecologically homogenised configuration, with reduced habitat diversity and diminished agricultural potential. Collectively, these states signal a profound transformation of Guidimouni's socio-ecological system toward a new, less desirable equilibrium.

4.1.4 Impacts

From the perspective of farmers, fishers and pastoralists, the most severe impacts are not ecological *per se* but livelihood-related,

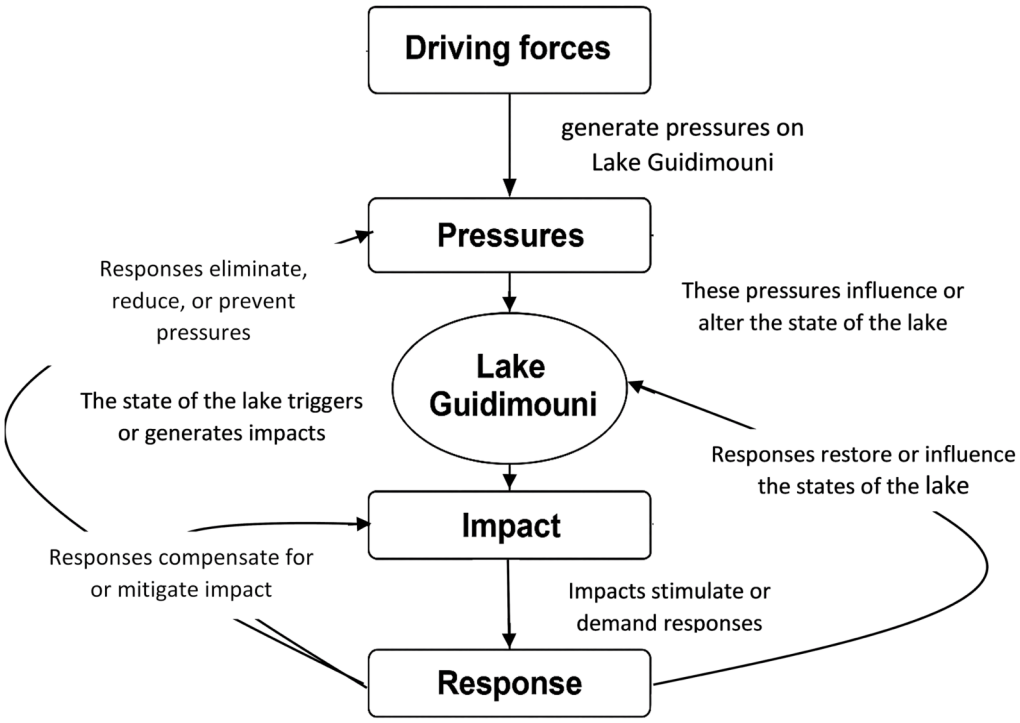


FIGURE 3
Operational DPSIR cycle linking climate drivers, ecological transitions and resilience responses in the Lake Guidimouni socio-ecological system. Schematic representation of the DPSIR (Drivers–Pressures–State–Impacts–Responses) cycle as explicitly operationalised for Lake Guidimouni to diagnose climate-driven socio-ecological change and identify leverage points for resilience. Drivers encompass both climatic and anthropogenic forcing factors, including increasing rainfall variability, intensifying flood–drought alternation, rising temperatures and land-use intensification. These drivers generate multiple Pressures, notably recurrent inundation, hydrological instability, sediment redistribution and the invasive expansion of *Typha domingensis*. The cumulative effects of these pressures reshape the ecological State of the lake, characterised by the transition from open-water and irrigated agricultural systems toward Typha-dominated marshlands, reduced habitat heterogeneity and declining land accessibility. These altered states translate into cascading Impacts on ecosystem functioning and human wellbeing, including loss of irrigable land, reduced agricultural productivity, biodiversity degradation, increased labour constraints, livelihood insecurity and heightened exposure to climate-related risks. Responses represent adaptive and mitigation strategies identified through the combined analysis of spatial evidence and convergent stakeholder perceptions. These include selective mechanical removal of *Typha domingensis*, hydrological regulation, adaptive land-use planning, livelihood diversification and participatory governance mechanisms aimed at restoring ecological balance and strengthening socio-ecological resilience. Bidirectional arrows highlight feedback loops and non-linear interactions within the DPSIR cycle, emphasising that responses may modify future pressures and drivers, thereby reinforcing or alleviating vulnerability. The figure synthesises the conceptual backbone of the DPSIR–GIS framework used in this study and underpins the spatial analyses, vulnerability mapping and resilience pathways developed for Lake Guidimouni between 2013 and 2024.

including loss of irrigable land, increased labour, obstruction of fishing activities and heightened exposure to water-related health risks. The impacts of these altered states cascade across both ecosystem and livelihood domains: degradation of the lacustrine ecosystem, income loss from submerged tree crops, livestock morbidity, increased water-borne disease, declining water quality, user conflicts, fish-stock depletion, obstruction of waterways and destruction of traditional fish traps by Typha, and the erosion of biodiversity and ecosystem services (Zungum et al., 2019; Chapagain and Raizada, 2017). These impacts illustrate how ecological degradation interacts with economic vulnerability, exposing local households to compounded climate-sensitive risks. These impacts underscore not only ecological vulnerability but also the fragility of local value chains and social resilience.

4.1.5 Responses

Proposed response measures largely reflect locally articulated priorities, particularly selective vegetation removal, hydrological regulation and livelihood diversification, which were repeatedly identified by stakeholders as feasible and socially acceptable interventions. Responses are the emergent countermeasures intended to mitigate impacts and restore balance. In Guidimouni these include: targeted mowing of aquatic vegetation; valorisation of harvested biomass into organic fertiliser, livestock feed or biochar; construction of hydrological regulation structures (HRSLs); promotion of income-generating activities (IGAs); awareness campaigns aligned with the National Wetland Policy and Local Convention for Lake Guidimouni; and groundwater-level monitoring and modelling of resurgence zones (Wetlands International, CARE Nederland, IWMI, and International Alert, 2020). These measures represent important levers for resilience-building, but their long-term effectiveness depends on institutional continuity, governance coordination, and sustained community engagement. While these measures embody genuine adaptive potential, they require sustained institutional support and multisectoral coordination. The overriding challenge is to craft inclusive, flexible governance able to adjust to evolving risks and

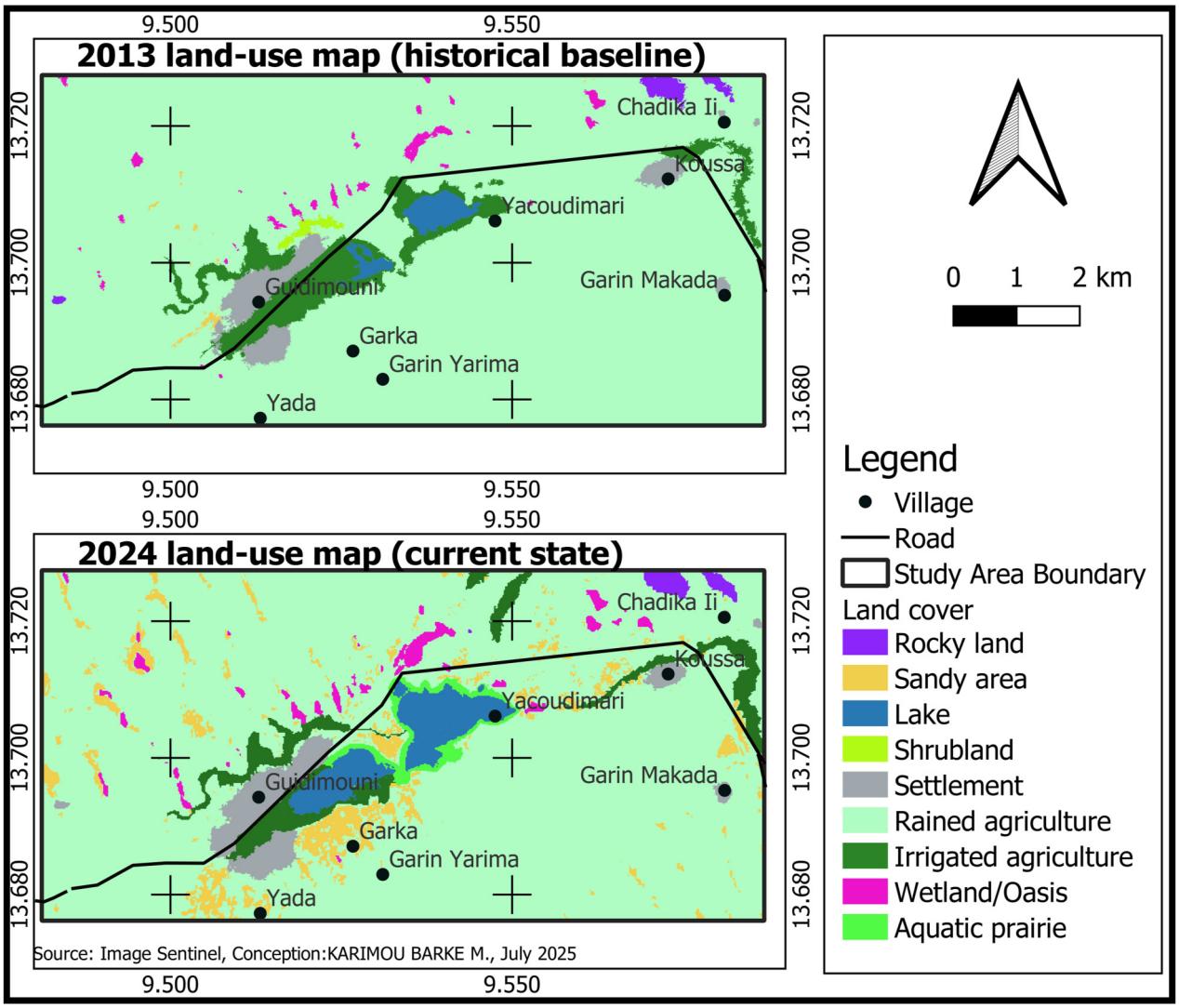


FIGURE 4
Long-term land-use transitions and climate-driven spatial reconfiguration around Lake Guidimouni (2013–2024). Spatio-temporal evolution of land-use and land-cover units surrounding Lake Guidimouni between 2013 and 2024, derived from object-oriented classification of multi-temporal satellite imagery. The figure illustrates pronounced landscape reconfiguration driven by the combined effects of climate variability and increasing anthropogenic pressure. Results reveal a marked expansion of permanent and semi-permanent water bodies, accompanied by the emergence and rapid growth of aquatic grasslands dominated by *Typha domingensis*, largely at the expense of irrigated agricultural areas. Concurrently, sandy and degraded surfaces expand substantially, indicating accelerating soil degradation and desertification processes in peripheral zones. Rainfed agriculture exhibits a net contraction, while settlements show moderate but steady growth, reflecting demographic pressure and land-use competition at the lake margin. These land-use trajectories provide direct spatial evidence of the State component of the DPSIR framework, capturing a structural ecological transition from productive agro-hydrological systems toward increasingly homogenised wetland and degraded terrestrial landscapes. When interpreted in conjunction with stakeholder perceptions and hydrological indicators, the observed trends highlight reinforcing feedbacks between flooding, invasive vegetation proliferation and declining land accessibility. The figure therefore constitutes a central analytical element for diagnosing vulnerability hotspots, quantifying exposure of livelihood systems, and informing targeted resilience responses within the DPSIR–GIS framework developed for Lake Guidimouni.

to integrate local knowledge with empirical data for truly sustainable management of Sahelian wetlands.

4.2 Adaptive DPSIR for Guidimouni's resilience

The DPSIR framework serves as a diagnostic scaffold for disentangling the entwined influence of natural and anthropogenic drivers, the pressures they impose, the state of the ecosystem, the cascading impacts, and the suite of responses either taken or proposed (Figure 3). Rather than serving as anecdotal evidence, stakeholder perceptions functioned as analytical inputs that reinforced the interpretation of spatial indicators, reduced interpretative uncertainty, and enhanced the legitimacy of identified vulnerability hotspots and response levers. In the context of Lake Guidimouni, this structured approach reveals not just linear causality but a web of feedbacks and leverage points critical for resilience building.

TABLE 5 Average annual spatial expansion rate of land use units around Lake Guidimouni from 2013 to 2024.

Land use units	Area (ha) in 2013	Area (ha) in 2024	Rate (%)
Rocky land	33.87	33.90	0.00
Sandy area	9.20	342.24	15.72
Lake	67.55	214.60	5.03
Aquatic grasslands	–	77.38	–
Shrubland	15.83	–	–
Settlement	148.98	195.96	1.19
Rainfed agriculture	5,839.33	5,282.50	−0.44
Irrigated agriculture	333.15	262.33	−1.04
Wetland/oasis	44.97	83.96	2.71

Rather than serving as anecdotal evidence, stakeholder perceptions functioned as analytical inputs that reinforced the interpretation of spatial indicators. Their integration reduced interpretative uncertainty, strengthened causal inference, and enhanced the legitimacy of identified vulnerability hotspots and response levers.

Our application illuminates how local perceptions, when mapped via the DPSIR logic, morph into systemic insights. Stakeholders' lived experience of changing water levels, invasive growth, and land conversion is not merely anecdotal—it becomes traceable into quantifiable pressure and state indicators. This bridges the oft-lamented gap between qualitative understanding and spatially explicit modelling (Baldwin et al., 2016).

Moreover, the DPSIR framing enables the identification of strategic levers—points where interventions can have disproportionate impact. For instance, recognizing that flood-driven inundation (a "pressure") accelerates Typha proliferation (a reinforcing state change) points directly to hydrological control or vegetation management as high-return responses.

In line with recent environmental systems research, our use of DPSIR is reflexive and adaptive: we respect its canonical categories, but allow them to interact nonlinearly. For example, we treat response measures themselves as potential future pressures (e.g., overharvesting, policy distortion), and feedback these into subsequent cycles. This echoes calls in contemporary literature to evolve DPSIR into more dynamic forms (e.g., temporal DPSIR) to better account for time lags and governance inertia (Hocherman et al., 2022).

Parallel to Obubu et al. (2022), who have demonstrated how DPSIR can harmonize stakeholder viewpoints with remote sensing and landscape change in African contexts, our analysis likewise leverages this integrative strength. In the case of Lake Guidimouni, this synthesis allows the identification of clear vulnerability hotspots where hydrological volatility, land-use intensification and Typha expansion converge.

Through this DPSIR-informed synthesis, we distill three salient insights:

1. Pressure clustering and spatial overlap: Zones under highest anthropogenic pressure (intensive irrigation, land clearing) often coincide with those most sensitive to hydrologic volatility—creating vulnerability hotspots.
2. State transitions locked by feedback loops: Once Typha establishes dominance (a state shift), it suppresses open water and native aquatic flora, thereby reinforcing hydrologic stress and sediment trapping—a self-amplifying cycle.
3. Response asymmetries: Not all levers are equal in effect. Targeted mowing or channel clearing yields more leverage than diffuse regulatory appeals; but institutional and social buy-in is essential for operational success.

4.3 Mapping of land-use units and observed changes

Annual spatial change rates illuminate the lake's territorial and environmental dynamics (Figure 4; Table 5):

- Rocky land remains stable, largely insensitive to short-term anthropogenic or climatic shifts.
- Sandy areas show spectacular expansion (+15.72%/year; +333 ha), signalling accelerated soil degradation, vegetation loss and intensifying desertification linked to wind erosion and declining rainfall (Hay et al., 2021).
- Water body invasion: 10.3 ha of open water already show high vulnerability to Typha invasion, jeopardising aquatic biodiversity, fishing and hydrological management (Tulbure et al., 2007).
- Aquatic grasslands now comprise 42.5% of irrigable zones bordering the lake, classed as highly vulnerable.
- Solid-waste deposition between residential and agricultural areas creates multiple risks: soil contamination, fertility decline, irrigation-water pollution, increased health hazards, and aesthetic/ecological degradation.

The spatial co-occurrence of Typha expansion, sand encroachment and declining agricultural land highlights a landscape undergoing accelerated ecological reconfiguration under combined climatic and anthropogenic pressures.

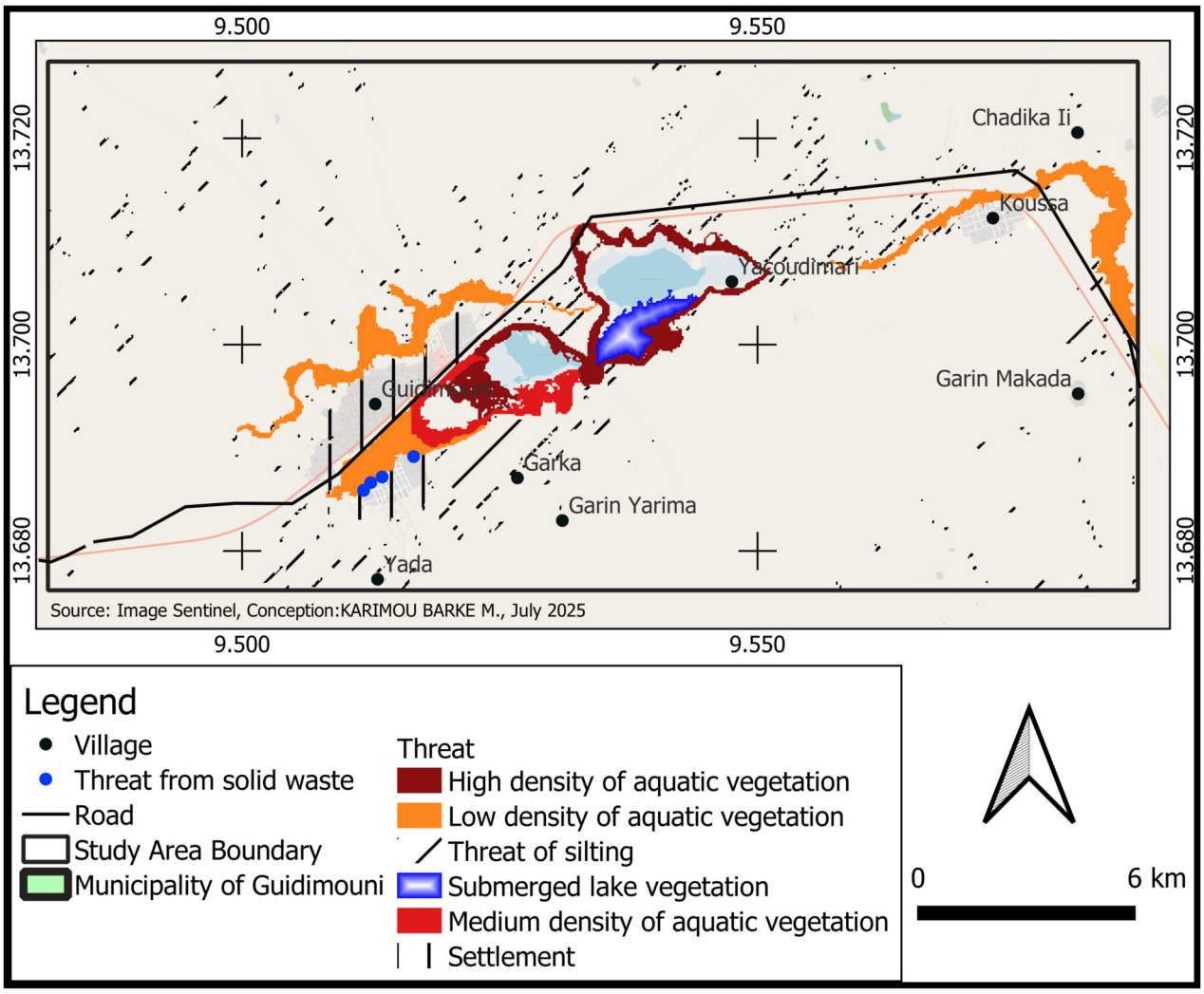


FIGURE 5
Spatial vulnerability of Lake Guidimouni to hydrological stress and *Typha domingensis* invasion under combined climatic and anthropogenic pressures. Integrated vulnerability map of Lake Guidimouni and its immediate surroundings, synthesising hydrological exposure, land-use sensitivity and invasive vegetation pressure within the DPSIR–GIS analytical framework. Vulnerability levels are derived from the spatial intersection of recurrent flooding patterns, land-cover transitions and the density of *Typha domingensis*, classified into low, moderate and high vulnerability zones based on ecologically meaningful thresholds. Areas classified as highly vulnerable correspond predominantly to lake-margin zones where intensified inundation and *Typha domingensis* dominance (>75% cover) have converted irrigated croplands into aquatic grasslands, severely constraining agricultural accessibility and ecosystem functionality. Moderately vulnerable zones reflect transitional landscapes exposed to periodic flooding and partial vegetation encroachment, where adaptive interventions may still prevent irreversible state shifts. Low-vulnerability areas remain comparatively stable, maintaining functional land-use systems and lower exposure to hydrological and biological pressures. This spatialisation captures the convergence of Pressures and State components of the DPSIR cycle and translates them into an operational diagnostic of socio-ecological risk. By integrating multi-temporal satellite observations (2013–2024) with field validation and convergent stakeholder perceptions, the map identifies priority hotspots for intervention and informs the targeting of resilience Responses, including selective *Typha* removal, hydrological regulation and adaptive land-use planning. The figure thus provides a decision-oriented representation of vulnerability, bridging biophysical evidence and governance-relevant insight for climate-resilient management of Sahelian wetland systems.

4.4 Vulnerability analysis of land-use units

Active dunes encroaching upon rain-fed fields and settlements act as vectors of aeolian sedimentation into the lake, threatening its hydraulic capacity and ecological quality if left unchecked (Hay et al., 2021; Iradukunda et al., 2020). Our spatial vulnerability analysis shows 64.9 ha of irrigated crops along the lake margins at moderate vulnerability to Typha expansion, and 185.6 ha at low vulnerability (Figure 5). About 32.5 ha of submerged orchards—particularly fruit trees inundated at >1 m depth—are suffering long-term yield losses, soil degradation and disruption of local value chains. Testimonies collected during surveys indicate that persistent flooding has rendered natron extraction impossible for over 20 years, exemplifying the enduring socio-economic footprint of hydrological change (Chapagain and Raizada, 2017). These combined stresses confirm that vulnerability is driven not only by biophysical

exposure but also by the erosion of livelihood options and reduced adaptive capacity among user groups.

4.5 Spatial autocorrelation and statistical significance of land-use transitions

To move beyond descriptive change detection, spatial autocorrelation analysis was conducted using Global Moran's I to assess clustering patterns of Typha expansion and flooded zones.

Results indicate significant positive spatial autocorrelation (Moran's I = 0.28, $p < 0.05$), confirming non-random clustering of vulnerability hotspots.

Getis-Ord Gi* statistics further identified statistically significant hotspots of land conversion concentrated along the western lake margin.

A Mann–Kendall trend analysis confirmed a statistically significant increasing trend in flooded area ($Z = 2.35$, $p < 0.05$).

Correlation analysis revealed a strong positive relationship between flooding extent and Typha proliferation ($r = 0.78$, $p < 0.01$).

Finally, a logistic regression model demonstrated that proximity to lake margin, elevation, and flood frequency significantly predict conversion of irrigated agriculture into aquatic grassland (Pseudo-$R^2 = 0.32$).

5 Conclusion

This study provides an integrated assessment of the socio-ecological vulnerability of Lake Guidimouni under accelerating climatic variability and cumulative anthropogenic pressures. By operationalizing the DPSIR framework through spatial modelling, remote sensing, and participatory calibration, we structured causal relationships linking drivers, ecological state shifts, and governance responses within a coherent analytical architecture.

The 2013–2024 spatio-temporal analysis reveals a marked ecological transition characterized by the expansion of aquatic and desertified zones, contraction of croplands, moderate urban growth, and the invasive proliferation of *Typha domingensis*. These dynamics signal a structural reconfiguration of the lake system, reflecting broader Sahelian wetland trajectories under climate-driven hydrological instability and increasing human pressure.

Beyond diagnosis, the study demonstrates that embedding stakeholder knowledge within the analytical workflow strengthens interpretative robustness and operational legitimacy. Local adaptive practices—such as biomass valorisation and community-based vegetation management—emerge as tangible resilience levers when aligned with spatial evidence and systemic modelling.

Taken together, the findings underscore the need for integrated natural-resource governance combining long-term hydrological monitoring, adaptive vegetation management, equitable water allocation, and participatory decision-making. Methodologically, the DPSIR–GIS architecture developed here provides a transferable decision-support framework for diagnosing and managing vulnerability in climate-sensitive dryland wetlands across the Sahel.

Lake Guidimouni thus emerges not merely as a vulnerable system, but as a sentinel landscape illustrating how science–society integration can anticipate tipping points and inform resilient territorial governance under intensifying climate change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the [patients/ participants OR patients/participants legal guardian/ next of kin] was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

MK: Writing – original draft, Writing – review and editing, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. BT: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. ME: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1726422/full#supplementary-material

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