



Hydroclimatic and Anthropogenic Threats to the Mangroves of Moanda in the Democratic Republic of the Congo

[Menaces hydroclimatiques et anthropiques pesant sur les mangroves de Moanda, en République démocratique du Congo]

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Abstract

Mangroves in Moanda, Democratic Republic of the Congo, are increasingly threatened by climate variability and human activities. This study aims to quantify hydroclimatic drivers and anthropogenic pressures influencing mangrove health using hydroclimatic and satellite-derived indices, and community-based surveys. The findings indicate that between 2000 and 2021, Normalized Difference Water Index (NDWI) exhibited significant variability (0.10–0.18), with moisture peaks in 2003 and 2005 followed by sharp declines in 2004, 2015, 2018, and 2021, indicating progressive hydric stress. Standardized Precipitation and Evapotranspiration Index (SPEI) and Climatic Moisture Index (CMI) trends (1990–2024) reveal alternating wet and dry periods, with severe droughts in 1992, 2001, 2010, and 2020, and wet years in 1993, 1999, 2005, and 2024, reflecting climate instability. Normalized Difference Vegetation Index remained relatively high (0.85–0.93) from 2000 to 2024, suggesting good vegetation cover but low resilience to climatic fluctuations. Anthropogenic pressures amplify these vulnerabilities: deforestation through shifting cultivation and artisanal logging shows the highest impact index (0.8), followed by unsustainable fishing (0.6), whereas oil extraction and settlements exert moderate impacts (≈ 0.4). The Pearson correlation suggests that hydroclimatic variability may influence socioeconomic activities, with drier conditions potentially associated with increased pressure on mangrove resources. These findings underscore the urgent need for integrated management strategies combining high-resolution climate monitoring, reforestation, regulation of logging and fishing, community engagement, and supportive policies to enhance mangrove resilience under increasing climate stress.

Keywords: Moanda mangroves, hydroclimatic threats, anthropogenic pressures, vegetation dynamics.

Résumé

Les mangroves de Moanda, en République Démocratique du Congo, sont de plus en plus vulnérables face à la variabilité hydroclimatique et aux pressions anthropiques. Cette étude vise à quantifier l'influence combinée des facteurs climatiques et des activités humaines sur la santé des écosystèmes de mangrove, en s'appuyant sur des indices climatiques et de télédétection, ainsi que des enquêtes communautaires. Il en ressort qu'entre 2000 et 2021, NDWI présente une forte variabilité (0,10–0,18), avec des pics d'humidité en 2003 et 2005 suivis de baisses marquées en 2004, 2015, 2018 et 2021, traduisant un stress hydrique croissant. Les tendances du SPEI et du CMI (1990–2024) révèlent une alternance de périodes humides et sèches, avec des sécheresses sévères en 1992, 2001, 2010 et 2020, et des années particulièrement humides en 1993, 1999, 2005 et 2024, indiquant une instabilité climatique. NDVI (2000–2024) reste globalement élevé (0,85–0,93), signe d'un bon couvert végétal, mais ses fluctuations lors des épisodes secs témoignent d'une faible résilience face aux contraintes climatiques. Les pressions anthropiques amplifient ces vulnérabilités : la déforestation par culture itinérante et exploitation artisanale du bois présente l'indice d'impact le plus élevé ($\approx 0,8$), suivie par la pêche non durable ($\approx 0,6$), alors que l'extraction pétrolière et les établissements humains ont des impacts modérés ($\approx 0,4$). La corrélation de Pearson suggère que la variabilité hydroclimatique pourrait influencer les activités socioéconomiques, les conditions plus sèches étant potentiellement associées à une pression accrue sur les mangroves. Ces résultats soulignent l'urgence d'intégrer des données climatiques à haute résolution dans les outils de planification et de mettre en œuvre des stratégies combinant reforestation, régulation des pratiques de pêche et de coupe, engagement communautaire et politiques publiques adaptées pour renforcer la résilience des mangroves face au stress climatique.

Mots-clés : Mangroves de Moanda, menaces hydroclimatiques, pressions anthropiques, dynamique de la végétation.

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1. Introduction

Mangrove forests in Africa cover over 3.2 million hectares, with approximately 1.5 million hectares located in the western Atlantic region stretching from Mauritania to Angola. Specifically, the central Atlantic coast (including parts of Central Africa) hosts around 0.4 million hectares (FAO, 2007; Tai et al., 2015; Basha, 2018). Within this broader African distribution, the mangroves of the Democratic Republic of the Congo (DRC), located in Moanda, constitute an important component of the West-Central African mangrove system. These mangroves hold a substantial fraction of global mangrove area and represent some of the planet's most efficient natural carbon sinks (Friess et al., 2012; Ajonina et al., 2014). Beyond storing large amounts of carbon, these forests protect coasts, support fisheries and livelihoods, and contribute to international climate and biodiversity goals (Lovelock et al., 2009; Etongo and Arrisol, 2021; CRREBaC, 2023).

Despite their ecological and socio-economic importance, Moanda's mangroves face increasing pressures from anthropogenic activities and climate change impacts, including extreme events such as flooding and droughts (Atyi, 2022). Consequently, their global importance lies not in size alone but in the outsized climate, ecological, and socio-economic benefits they provide relative to their limited area, and in the heavy losses that would occur if they are degraded or destroyed.

To date, existing studies in Africa indicate that mangrove ecosystems are increasingly affected by interacting anthropogenic disturbances, including harvesting, pollution, urbanization, and land-use conversion, and climate-related stressors such as sea-level rise, altered precipitation, and temperature variability (Goldberg et al., 2020; Naidoo, 2023). However, integrated quantitative assessments remain limited, particularly in the Moanda's mangroves, where insufficient long-term ecological datasets constrain evidence-based management and conservation planning (UNEP, 2007; Ajonina et al., 2014).

This study aims to integrate hydroclimatic trends and their impacts on mangrove health with anthropogenic pressures in order to propose recommendations for sustainable mangrove management and inform future conservation actions.

We hypothesize that climate variability and human activities interact to increase mangrove vulnerability. To address these objectives, we adopted an integrated approach combining spatial analysis of hydroclimatic and satellite-derived indices with community-based surveys to quantify pressures and identify actionable management strategies (GWP and WMO, 2016).

2. Matériel et méthodes

2.1. Study area

Moanda's mangroves are located within the Mangrove Marine Park, situated on the northern bank of the mouth of the Congo River near the towns of Banana and Moanda in the territory of Moanda, and extending to approximately 5°45'S latitude and 12°4'E longitude (figure 1).

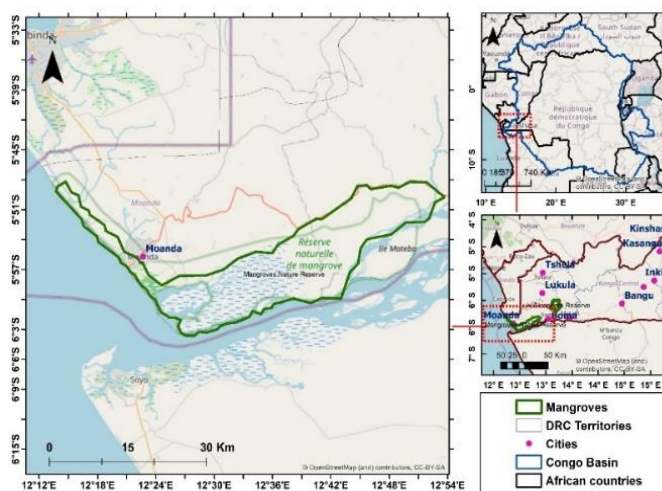


Figure 1. Location of the Moanda Mangrove Marine Park in the DRC

The Congo River flows through the provinces of the Kongo Central and along the province of Kongo Central before reaching its mouth on the Atlantic Ocean (Trigg & Tshimanga, 2020). The hydrography of the Moanda area covers a small part of the DRC, extending along the Atlantic coast and including the deltaic zone at the mouth of the Congo River, the river banks up to Boma, and the low-lying coastal plateau (about 100 metres) known as the 'hinterland'. The mangrove area lies within the Köppen AW5 climate zone, which is characterized by an average annual rainfall of at least 1000 mm and an average temperature of 22°C, with extremes ranging from 19°C to 32°C. Annual rainfall averages 772 mm, but varies considerably from year to year. The humid tropical

climate has distinct rainy and dry seasons, and the cold Benguela Current particularly influences the coastal region (CRREBaC, 2023). The inclusion of this area is supported by both climatic and edaphic factors. The coastal zone has a population of about 1,300,000, of which Moanda and Banana are the two main towns, each with an estimated population of 60,000 (MECN-EF, 2001). Moanda, with 57,708 inhabitants in 1994, hosts a significant part of the coastal population, while the rural areas are less densely populated, with about 10 inhabitants per square kilometre. Economically, the coastal zone differs from the rest of the country as it is the only area with a developed oil industry. Over 90% of the wealth in Moanda, Banana and the surrounding towns comes from the oil sector in the form of wages and services.

2.2. Conceptual framework

The conceptual framework developed for this study (figure 2) links hydroclimatic variability, anthropogenic pressures, and mangrove ecosystem conditions in Moanda (Tshimanga et al., 2021). The framework includes three main components: (i) hydroclimatic variables such as rainfall variability, evapotranspiration, soil moisture, flooding, and drought; (ii) land-cover dynamics reflecting changes in mangrove vegetation and ecosystem conditions; and (iii) socio-economic factors, including dependence on mangrove resources, agricultural activities, fishing practices, and oil-related activities. Anthropogenic and hydroclimatic factors may interact and contribute to mangrove degradation through deforestation, habitat alteration, salinity changes, erosion, and resource depletion. The framework provides a basis for analyzing the combined effects of environmental and human pressures on mangrove ecosystems and for supporting sustainable management strategies.

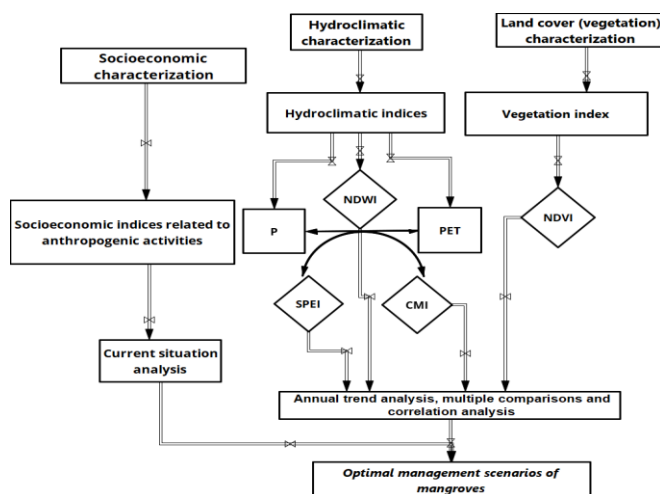


Figure 2. Conceptual framework of the study

2.3. Study period and data sources

Hydroclimatic data were analyzed for the period 1990-2024, while vegetation indices covered 2000-2021. NDVI and NDWI were derived from Landsat 7 ETM+ and Landsat 8 OLI imagery (30 m resolution), accessed via USGS Earth Explorer. SPEI and CMI were computed using precipitation and PET data from the Climatic Research Unit (CRU) Time-Series (TS) version 4.06 datasets (0.5° spatial resolution).

2.4. Data available and analysis

The indices employed in this study offer a robust representation of hydroclimatic and anthropogenic threats affecting mangrove ecosystems. The Standardized Precipitation Evapotranspiration Index (SPEI) is used to evaluate drought conditions by accounting for the balance between precipitation (P) and potential evapotranspiration (PET), with lower values signaling freshwater deficits that increase salinity stress in mangroves. The SPEI is calculated using the Thornthwaite water balance method, where the climatic water balance:

$$D=P-PET$$

$D=P-PET$ is standardized over time using a log-logistic probability distribution (Vicente-Serrano, 2010).

The Climatic Moisture Index (CMI) is a widely used indicator for assessing the balance between available moisture and atmospheric demand across different ecosystems. It reflects the relative wetness or dryness of a climate, with positive CMI values indicating humid conditions and negative values indicating arid or moisture-deficit conditions that can stress mangrove ecosystems by reducing freshwater availability and increasing salinity (Karam, et al., 2022). The CMI is calculated using the formula:

$$CMI = \frac{P - PET}{PET}$$

Where P = Precipitation and PET = Potential Evapotranspiration. This index normalizes the climatic water balance by expressing the surplus or deficit of precipitation relative to atmospheric moisture demand. A CMI close to zero implies a climatic equilibrium, while strongly negative values signal drought-prone environments potentially harmful to mangroves due to increased evapotranspiration and reduced freshwater inputs.

The Normalized Difference Water Index (NDWI) detects surface water presence and moisture content in vegetation, using the formula:

$$NDWI = \frac{NIR - SWRI}{NIR + SWRI}$$

Where NIR is the near-infrared reflectance and SWIR is the shortwave infrared reflectance (McFeeters, 1996). Similarly, the Normalized Difference Vegetation Index (NDVI) assesses vegetation health and density, with values closer to 1 indicating healthy vegetation (Meneses-Tovar, 2012). It is calculated using the formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where RED is the red reflectance.

The remaining indices Households practicing shifting cultivation (SHC), Households using unsustainable fishing methods (USFM), Households harvesting wood by hand (WHB), Households reporting increase in oil extraction (OEA), Households reporting general increase in activities (GIA), Households reporting high levels of human occupation (HHO) are derived from field-based household survey data and expressed as simple proportions:

$$I = \frac{P_0}{P}$$

Where P is the number of households reporting the activity and P₀ is the total number surveyed.

Collectively, these indices, sourced from satellite data and national peatland surveys (CRREBaC, 2023). Field investigations were conducted from June to September 2023 using purposive sampling with 100 households based on the Yamane formula for sample size determination at 95% confidence level, along with interviews of 30 key informant interviews were conducted with farmers, fishers, and oil industry workers. Anthropogenic pressure indices were computed as proportions of households reporting specific activities (e.g., shifting cultivation, unsustainable fishing, artisanal logging)

The use of Landsat imagery (30 m resolution) limits fine-scale detection of mangrove degradation. Global climate datasets may not fully capture local variability. Household surveys are subject to recall bias, and NDVI/NDWI estimates can be affected by seasonal cloud cover.

3. Résultats

3.1. Hydroclimatic and vegetation indices

Figure 3 shows that between 2000 and 2021, the NDWI shows greater variability, with values ranging from about 0.10 to 0.18. This variability reflects

significant changes in vegetation moisture or surface water availability. Peaks in relative moisture were observed in 2003 and 2005, followed by notable decreases, particularly in 2004, 2015, 2018, and a sharp decrease in 2021. The progressive decline of the NDWI towards the end of the series may indicate a trend towards reduced moisture or water availability, possibly associated with increasing water stress or recurrent droughts. Thus, the NDWI trend suggests a slight degradation of hydric conditions over time.

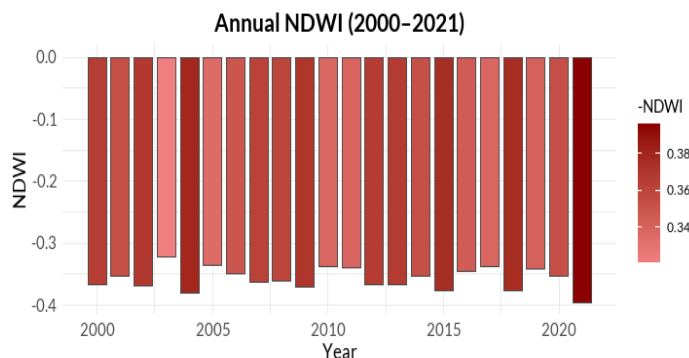


Figure 3. Interannual variability of the NDWI

Figure 4 shows the interannual variability of the SPEI. It shows significant fluctuations from 1990 to 2024, reflecting shifts between wet and dry conditions over the years. Positive values indicate wetter than normal conditions, while negative values represent drought episodes. A clear alternation of wet and dry periods is observed, with notable droughts in 1992, 2001, 2010, and 2020, and particularly wet years in 1993, 1999, 2005, and 2024. Although no clearly defined long-term trend emerges, recent years tend to show slightly drier conditions, highlighting the usefulness of this indicator for climate monitoring within the ecohydrological system of the Moanda mangroves.

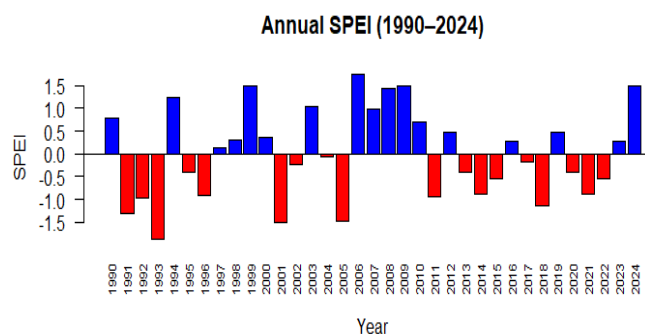


Figure 4. Interannual variability of the SPEI 12-month

Figure 5 shows the annual variations of the Climate Moisture Index (CMI) from 1990 to 2024. Overall, the CMI shows significant variation over the years, with no clear long-term upward or downward trend. Notable moisture peaks are observed around 1995, 1999, 2006, and 2024, indicating particularly wet years. Conversely, years such as 1993, 2002, and 2005 show significant decreases in the CMI, indicating drier periods. These variations reflect potential climate instability, with alternating wet and dry years rather than a consistent linear pattern

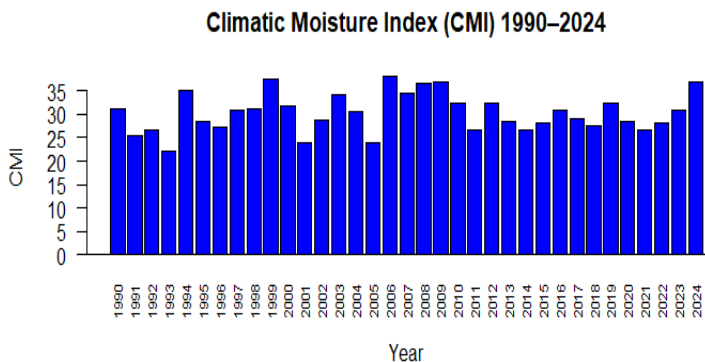


Figure 5. Interannual variability of the CMI

Figure 6 shows that the annual NDVI remains generally stable between 2000 and 2021, with consistently high values (between 0.85 and 0.93), indicating good vegetation cover. Some downward fluctuations are observed, especially in 2003, 2005 and 2010, probably related to the prevailing climatic conditions, while peaks occur in 2002, 2009, 2018 and especially in 2021. These fluctuations indicate low vegetative resilience and high sensitivity of mangrove areas to climatic factors.

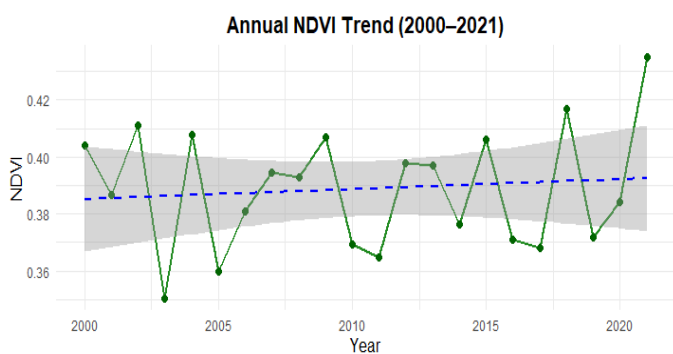


Figure 6. Interannual variability of the NDVI

3.2. Socioeconomic indices

In terms of indices linked to human activities (Figure 7), deforestation practices such as shifting cultivation (SHC), unsustainable fishing methods (USFM) and artisanal logging (WHB) have a

significant impact, with standardised values close to the critical situation (0.6-0.8). In contrast, human pressure (0.4), increased activity (GIA) has very lower impact (0.1), oil extraction (OEA) and human settlements (HHO) have a moderate impact (0.4).

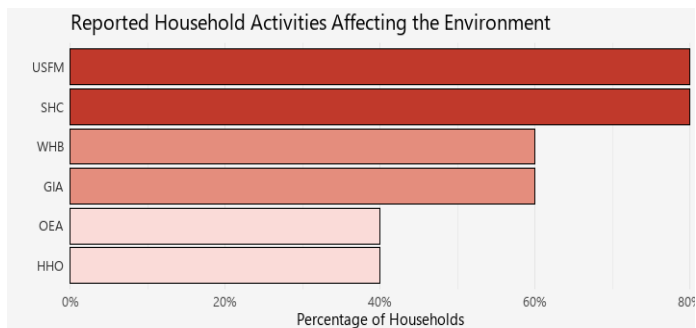


Figure 7. Socioeconomic indices

	NDWI	SPEI	CMI	NDVI	USFM	SHC	WHB	GIA	OEA	HHO
NDWI	1.00	0.78	-0.52	0.67	-0.62	-0.45	-0.66	0.58	-0.41	-0.35
SPEI	0.78	1.00	-0.65	0.81	-0.76	-0.58	-0.78	0.68	-0.52	-0.44
CMI	-0.52	-0.65	1.00	-0.62	0.55	0.42	0.64	-0.48	0.36	0.28
NDVI	0.67	0.81	-0.62	1.00	0.71	0.56	0.69	-0.65	0.49	0.38
USFM	-0.62	-0.76	0.55	0.71	1.00	0.63	0.71	-0.56	0.48	0.39
SHC	-0.45	-0.58	0.42	0.56	0.63	1.00	0.66	-0.49	0.44	0.31
WHB	-0.66	-0.78	0.64	0.69	0.71	0.66	1.00	-0.61	0.53	0.42
GIA	0.58	0.68	-0.48	-0.65	-0.56	-0.49	-0.61	1.00	-0.57	-0.46
OEA	-0.41	-0.52	0.36	0.49	0.48	0.44	0.53	-0.57	1.00	0.68
HHO	-0.35	-0.44	0.28	0.38	0.39	0.31	0.42	-0.46	0.68	1.00

Figure 8. Pearson correlation matrix between hydroclimatic indices and socio-economic indicators

4. Discussion

The aim of this study was to quantify the combined influence of hydroclimatic drivers and anthropogenic pressures on mangrove condition in Moanda and to test the hypothesis that climate variability and human activities interact to increase vulnerability. The ecohydrological system of the Moanda mangroves reveals complex interactions between vegetation dynamics, climatic moisture variability and anthropogenic factors (Figure 8). The strong correlations among the hydroclimatic indices, particularly between SPEI and NDVI (r=0.81), may suggest that improved hydroclimatic conditions are associated with healthier mangrove vegetation cover. Similarly, the positive correlations between NDWI and SPEI (r=0.78) and between NDWI and NDVI (r=0.69) could indicate that higher water availability supports

favorable vegetation conditions, whereas the negative correlation between CMI and SPEI ($r=-0.65$) may reflect differences between moisture conditions and water deficit periods (Vicente-Serrano, 2010). Negative correlations between hydroclimatic indices (NDWI and SPEI) and some socioeconomic activities, including USFM ($r=-0.62$) and WHB ($r=-0.71$), may suggest that drier conditions are associated with increased pressure on environmental resources. However, these relationships should be interpreted cautiously, as correlation does not necessarily imply causation (Zhao et al., 2021).

Integrating high-resolution drought indicators like SPEI with NDVI and NDWI allows for more precise monitoring of mangrove responses to climatic stressors. Climate change represents a significant and growing threat to mangrove ecosystems globally. For instance, the Intergovernmental Panel on Climate Change (IPCC, 2022) reports that African coastal ecosystems are highly vulnerable to even moderate warming, with mangroves particularly exposed to sea-level rise, increased cyclone frequency, and sedimentation disruption. According to the Global Mangrove Watch, approximately 50% of the world's mangroves are located in provinces facing moderate to high anthropogenic and climate-related risks (Worthington, et al., 2020).

While climate drivers such as rising temperatures and shifting rainfall patterns affect mangrove viability, global assessments agree that direct anthropogenic pressures such as, deforestation, coastal development, and aquaculture, remain the primary cause of mangrove loss (UNEP, 2023). For example, urban expansion in parts of Central and West Africa, including the Gulf of Guinea, has led to an annual mangrove loss of more than 3% in some areas (Spalding & Collins, 2014).

In Moanda, anthropogenic pressures are predominantly local and resource-based. According to Kangudia et al. (2024), small-scale land-use practices such as shifting cultivation, artisanal logging, and charcoal production are the primary drivers of deforestation (Kangudia & Mumbere, 2024). Impact indices derived from field data show that these practices approach critical thresholds (around 0.8 on a standardized impact scale), far exceeding those associated with industrial activity or urban expansion (values between 0.1 and 0.4). Despite the presence of offshore oil operations (Mayala, 2020), their spatial footprint appears more localized compared to diffuse

pressures from livelihood-based resource exploitation (Miñano & Ngoma, 2022). These pressures have led to widespread ecosystem degradation, including biodiversity decline, soil salinization, and increased shoreline erosion. Such environmental losses also jeopardize the livelihoods of local populations who rely heavily on mangrove resources for food security, fuel, and flood protection (WWF, 2023). Moanda's mangrove dynamics mirror broader Central African trends of degradation but with unique local conditions. While Cameroon and Republic of Congo face severe losses from urbanization and industrial expansion (Spalding et al., 2014; Rainforest Foundation UK, 2023), and Gabon shows high soil carbon stocks with site-specific resilience (Alongi, 2008; USDA Forest Service, 2022), Moanda combines resource-driven deforestation and climate variability with distinctive hydrological and salinity patterns shaped by the Congo River mouth and Benguela Current (IPCC, 2022; CRREBaC, 2023).

Given these findings, a combination of ecological monitoring, community-based management, and policy support is needed to ensure the sustainable future of Moanda's mangroves (Alongi, 2008). Key recommendations include: Enhanced Monitoring; protected area expansion; community engagement; climate resilience building; policy and governance strengthening. By integrating ecological data with climate risk assessments and addressing high-impact local drivers, policymakers and conservation practitioners can better safeguard the ecological integrity of the Moanda mangroves while promoting climate adaptation and community resilience.

5. Conclusion

This study represents one of the few integrated assessments of hydroclimatic variability and anthropogenic pressures on mangroves in Central Africa, combining hydroclimatic and satellite-derived indices (NDVI, NDWI, SPEI, and CMI) with socioeconomic data. The aim of this study was to investigate the interactions between hydroclimatic factors, anthropogenic uses, and vegetation conditions within the Moanda mangroves to better understand the ecosystem's vulnerability mechanisms. The methodological approach combined the analysis of satellite data to assess moisture levels, vegetation health, and drought stress with field investigations including surveys of 100 households and interviews

with 30 key stakeholders from the agricultural, fishing, and extractive sectors.

Results reveal that soil moisture strongly influences vegetation health, as shown by the very high correlation between NDVI and NDWI, while SPEI exerts a moderate effect and CMI a weak influence. On average, NDWI values ranged from 0.10 to 0.18 between 2000 and 2021, indicating a progressive decline in hydric conditions, while NDVI remained relatively high (0.85–0.93), suggesting good vegetation cover but low resilience to climatic fluctuations. SPEI and CMI trends (1990-2024) showed alternating wet and dry periods, with severe droughts in 1992, 2001, 2010, and 2020, and wet years in 1993, 1999, 2005, and 2024, reflecting climate instability rather than a linear trend.

Anthropogenic pressures amplify these vulnerabilities: deforestation through shifting cultivation and artisanal logging shows the highest impact index (0.80), followed by unsustainable fishing (0.60), while oil extraction and human settlements exert moderate impacts (0.40). The findings suggest that anthropogenic disturbance may exacerbate the effects of hydroclimatic stress by reducing canopy cover and weakening ecological resilience. Furthermore, the findings indicate potential interactions between hydroclimatic variability and socioeconomic activities, with drier conditions potentially associated with increased pressure on mangroves. Consequently, degraded mangrove stands appear less capable of recovering from drought events, indicating a synergistic interaction between climate variability and local human pressures.

These findings advocate for an integrated and forward-looking management strategy for the Moanda mangroves. It is essential to enforce regulations on logging and fishing, and strengthen community-based monitoring, enhance environmental monitoring using high-resolution climate indicators, promote ecological restoration, incorporate traditional knowledge, and establish inclusive policies that support the resilience of coastal ecosystems. The long-term sustainability of these wetlands will depend on the capacity to harmonize conservation efforts, climate adaptation, and sustainable territorial development. Future research should focus on long-term hydroclimatic monitoring, predictive modeling of mangrove vulnerability under climate scenarios, and socio-economic studies to support sustainable livelihoods. This study acknowledges limitations related to spatial

resolution, global climate datasets, and potential recall bias in household surveys.

Without intervention, the combined effects of climate stress and human pressures could lead to irreversible mangrove loss in Moanda, jeopardizing biodiversity, coastal protection, and community resilience.

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Conflict of interest

The authors declare no conflict of interest.

Ethics considerations

This study did not involve human or animal subjects. However, data collection in the field adhered to all applicable environmental research ethics guidelines. All field activities were conducted with prior authorization from local and provincial environmental authorities. Community engagement followed principles of free, prior, and informed consent where applicable.

Author contributions

G.-S.K.L.: contributed to conceptualization, methodology, software, data collection, formal analysis, and writing, review, and editing.

F. N.: contributed to data collection and formal analysis.

M. K. W.: contributed to data collection.

R. M. T.: contributed to conceptualization and supervision.

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