

Hydrological And Ecological Indicators Of Peatland Vulnerability In Tropical Watersheds: Integrating Remote Sensing And Biogeochemical Approaches In The Democratic Republic Of Congo

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ABSTRACT

The Cuvette Centrale peatlands of the Democratic Republic of Congo constitute the world's largest tropical peatland complex, storing an estimated 29 billion tonnes of carbon. Yet these globally significant ecosystems remain among the least studied and most vulnerable to environmental change. This study examines the integration of hydrological and ecological indicators for assessing peatland vulnerability in tropical watersheds, synthesizing remote sensing, biogeochemical, and hydrological modelling approaches applicable to the DRC's peatlands. The analysis reveals that inundation dynamics constitute the primary control on greenhouse gas emissions from peatlands, with daily water level mapping at 100 m spatial resolution now achievable using ALOS-2 PALSAR-2 radar data calibrated against field measurements. Remote sensing indicators, particularly the Normalized Burn Ratio (NBR), demonstrate significant correlation with peat carbon stocks (Spearman's $\rho = -0.664$, $p < 0.05$) and hydrogen index values ($\rho = 0.7$, $p < 0.05$), enabling detection of degradation in upper peat profiles. Biogeochemical indicators derived from Rock-Eval pyrolysis, including the immature organic matter index (I-index) and refractory organic matter index (R-index), provide complementary evidence of enhanced decomposition in disturbed sites. The study identifies four categories of vulnerability indicators applicable to DRC's watersheds: hydrological indicators (water table depth, inundation extent, baseflow), biogeochemical indicators (carbon density, decomposition indices, nutrient status), remote sensing indicators (NBR, radar backscatter, vegetation indices), and anthropogenic indicators (deforestation rate, protected area status, concession overlap). Integration of these multi-scalar indicators offers a comprehensive framework for monitoring peatland vulnerability and guiding conservation strategies.

Keywords: Peatland Vulnerability; Hydrological Indicators; Remote Sensing; Biogeochemical Indicators; Cuvette Centrale; Democratic Republic of Congo; Inundation Dynamics; Carbon Storage; Rock-Eval Pyrolysis; Radar Remote Sensing; Ecosystem Monitoring; Tropical Peatlands.

RESUME

Les tourbières de la Cuvette Centrale en République démocratique du Congo constituent le plus grand complexe de tourbières tropicales du monde, stockant environ 29 milliards de tonnes de carbone. Pourtant, ces écosystèmes d'importance mondiale restent parmi les moins étudiés et les plus vulnérables aux changements environnementaux. Cette étude examine l'intégration d'indicateurs hydrologiques et écologiques pour l'évaluation de la vulnérabilité des tourbières dans les bassins versants tropicaux, en synthétisant les approches de télédétection, biogéochimiques et de modélisation hydrologique applicables aux tourbières de la RDC. L'analyse révèle que la dynamique d'inondation constitue le principal contrôle des émissions de gaz à effet de serre des tourbières, avec une cartographie quotidienne du niveau d'eau à une résolution spatiale de 100 m désormais réalisable à l'aide des données radar ALOS-2 PALSAR-2 calibrées sur des mesures de terrain. Les indicateurs de télédétection, en particulier le Rapport Normalisé de Brûlure (NBR), démontrent une corrélation significative avec les stocks de

carbone des tourbières (ρ de Spearman = -0,664, $p < 0,05$) et les valeurs d'indice d'hydrogène ($\rho = 0,7$, $p < 0,05$), permettant la détection de la dégradation dans les profils supérieurs de tourbe. Les indicateurs biogéochimiques dérivés de la pyrolyse Rock-Eval, notamment l'indice de matière organique immature (I-index) et l'indice de matière organique réfractaire (R-index), fournissent des preuves complémentaires de décomposition accrue dans les sites perturbés. L'étude identifie quatre catégories d'indicateurs de vulnérabilité applicables aux bassins versants de la RDC : les indicateurs hydrologiques (profondeur de la nappe phréatique, étendue des inondations, débit de base), les indicateurs biogéochimiques (densité du carbone, indices de décomposition, état nutritionnel), les indicateurs de télédétection (NBR, rétrodiffusion radar, indices de végétation) et les indicateurs anthropiques (taux de déforestation, statut des aires protégées, chevauchement des concessions). L'intégration de ces indicateurs multi-échelles offre un cadre complet pour le suivi de la vulnérabilité des tourbières et l'orientation des stratégies de conservation.

Mots-clés : Vulnérabilité des Tourbières; Indicateurs Hydrologiques; Télédétection; Indicateurs Biogéochimiques; Cuvette Centrale; République Démocratique du Congo; Dynamique d'Inondation; Stockage du Carbone; Pyrolyse Rock-Eval; Télédétection Radar; Suivi des Écosystèmes; Tourbières Tropicales.

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1. INTRODUCTION

The Cuvette Centrale peatlands of the Democratic Republic of Congo represent one of Earth's most significant natural carbon stores, yet they remain among the least studied and most vulnerable ecosystems on the planet. Spanning an estimated 167,600 square kilometres across the central Congo Basin, these peatlands store approximately 29 billion tonnes of carbon, equivalent to roughly three years of global fossil fuel emissions. The discovery and mapping of these peatlands fundamentally reshaped scientific understanding of the Congo Basin's ecological significance, revealing that the region holds approximately 36% of all tropical peatlands and roughly 28% of the world's tropical peat carbon.

The vulnerability of these ecosystems arises from multiple interacting pressures. Climate projections indicate that temperatures in the Congo Basin could increase by 1.5-2°C by the end of the century, with more frequent and intense heatwaves and greater seasonal variations in rainfall, including prolonged drought periods. Anthropogenic pressures are intensifying, with deforestation in the DRC exceeding 1 million hectares per year. The interaction of these pressures creates potential for cascading consequences: peatland degradation would release large amounts of CO₂ into the atmosphere, contributing to climate change and potentially creating feedback loops that accelerate further degradation.

Effective monitoring and assessment of peatland vulnerability requires integrated approaches that combine hydrological, ecological, and biogeochemical indicators. Remote sensing offers the capacity to monitor peatland condition across large spatial scales, while biogeochemical analysis provides detailed information on carbon dynamics and degradation processes. The integration of these approaches is essential for identifying priority areas for conservation and restoration, and for tracking the effectiveness of management interventions.

This study examines the integration of hydrological and ecological indicators for assessing peatland vulnerability in tropical watersheds, synthesizing remote sensing, biogeochemical, and hydrological modelling approaches applicable

to the DRC's peatlands. The research questions guiding this study are: What are the key hydrological and ecological indicators of peatland vulnerability applicable to tropical watersheds? How can remote sensing and biogeochemical approaches be integrated for monitoring peatland condition? What are the strengths and limitations of different indicators for assessing vulnerability in the DRC's Cuvette Centrale?

2. LITERATURE REVIEW

The literature on tropical peatlands, remote sensing, and biogeochemical approaches provides a rich foundation for analysing the integration of indicators for assessing peatland vulnerability.

2.1 The Cuvette Centrale Peatlands: Characteristics and Carbon Storage

The Cuvette Centrale peatlands represent the world's largest tropical peatland complex. Research by Crezee and colleagues, involving extensive field surveys in the DRC, produced a 50-metre resolution map showing that the central Congo peatlands cover 167,600 square kilometres (95% confidence interval: 159,400-175,100 square kilometres). Using field data, this research derived the first basin-wide maps of peat thickness a mean of 1.7 metres with a standard deviation of 0.9 metres and a maximum of 5.6 metres and peat carbon density a mean of $1,712 \pm 634$ Mg C per hectare, with a maximum of 3,970 Mg C per hectare. These field-based constraints give high confidence that the central Congo Basin holds the world's largest tropical peatland complex, storing approximately 36% of all tropical peatlands and roughly 28% of the world's tropical peat carbon.

A critical finding of this research is that peatlands in the DRC occur in geomorphologically distinct settings from those previously documented in the Republic of Congo. In the Republic of Congo, peatlands are found mostly in interfluvial basins, bounded from rivers by patches of terra firme forest and savanna, and are largely rain-fed, receiving minimal river water input. In contrast, some peatlands in the DRC are located immediately adjacent to rivers and characterized by high inundation levels, representing a river-influenced peatland type.

The distribution of peat carbon across the central Congo Basin is uneven. The DRC's Équateur Province holds the largest share, with an estimated 10.7 Pg C, followed by Mai-Ndombe (5.2 Pg C), Tshuapa (2.1 Pg C), Sud-Ubangi (1.0 Pg C), and Mongala (0.6 Pg C). Protected area coverage is limited, with only 8% of central Congo peat carbon lying within national protected areas, while 26% lies within logging, mining, or palm oil concessions.

2.2 Inundation Dynamics and Hydrological Controls

Inundation dynamics constitute the primary control on greenhouse gas emissions from peatlands. Research by Georgiou on the Cuvette Centrale wetlands used ALOS-2 PALSAR-2 remotely sensed radar data to assess the spatial and temporal dynamics of inundation across the region. This involved first determining a relationship between water level and radar backscatter using field collected measurements of water table depth. Correlative statistics were used to categorise locations as rainfed versus those which receive additional water inputs from river flooding. The research found that most of the rainfed peatlands exist to the west of the Congo River, while river-influenced peatlands characterize the eastern portion.

The hydrological modelling study by Apers and colleagues used enhanced land surface modelling and SMOS L-band data assimilation to improve understanding of hydrological dynamics in the Cuvette Centrale. The researchers

updated PEATCLSM hydrological parameters for the Congo Basin peatlands using a new event-based approach named HYPA_SAT, significantly reducing the dry bias present in water level simulations. The assimilation of SMOS L-band brightness temperature observations further enhanced the accuracy of water level estimates, indicated by improved temporal correlations with in situ data. The data assimilation results highlighted the sensitivity of the hydrology of the Congo Basin peatlands to local and upstream rainfall variability, as well as river dynamics.

2.3 Remote Sensing of Peatland Degradation

Remote sensing offers the capacity to detect peatland degradation across large spatial scales. Research by Brown and colleagues combined organic geochemical analysis by Rock-Eval pyrolysis of peat collected from sites with different land management history and optical remote sensing products to assess if remotely sensed data could be used to predict peat conditions and carbon storage. The study used the North Selangor Peat Swamp forest, Malaysia, as the model system.

The research found that peat core sub-samples and litter collected from Fire Affected, Disturbed Forest, and Managed Recovery locations had different decomposition profiles than Central Forest sites. Rock-Eval pyrolysis of the upper peat profiles showed that surface peat layers at disturbed locations had lower immature organic matter index (I-index) values (average I-index range in upper section 0.15 to -0.06) and higher refractory organic matter index (R-index) (average R-index range in upper section 0.51 to 0.65) compared to Central Forest sites, indicating enhanced decomposition of the surface peat.

Crucially, the research found that in the top 50 cm section of the peat profile, carbon stocks were negatively related to the Normalized Burn Ratio (NBR), a satellite-derived parameter (Spearman's $\rho = -0.664$, $S = 366$, $p\text{-value} = <0.05$), while there was a positive relationship between the hydrogen index and the Normalized Burn Ratio profile (Spearman's $\rho = 0.7$, $S = 66$, $p\text{-value} = <0.05$). This suggests that remotely sensed products can detect degradation of peat in the upper peat profile, providing a powerful tool for identifying degraded peatland areas and supporting identification of areas for conservation and restoration.

2.4 Hydrological Modelling Approaches

Hydrological modelling offers a valuable opportunity to understand peatland dynamics and vulnerability. Research by Segah and colleagues used hydrological modelling to assess the impact of peat restoration in the Sebangau-Katingan Peat Hydrological Unit, Central Kalimantan. The study used the flood hydrograph method to review flow characteristics in restored and non-restored areas, finding that restored areas had larger base flow compared to non-restoration areas. Base flow, a steady discharge originating from natural storage, serves as an indicator of the availability and sustainability of river water and is influenced by land cover along the watershed.

Research on tropical peatland hydrology in Southeast Asia has demonstrated that evapotranspiration represents the dominant water loss, accounting for 62-98% of annual rainfall across different land-cover types. Conversion from peat swamp forest to managed areas caused approximately 1% lower evapotranspiration, approximately 6% higher runoff, and negligible differences in storage change under the same rainfall inputs. In contrast, interannual rainfall variability produced up to eightfold differences in runoff and approximately 120 mm reversal in storage change between dry and wet years.

2.5 Biogeochemical Indicators of Peatland Condition

Biogeochemical indicators provide detailed information on peat condition and degradation processes. Research by Onzeli and colleagues in the Bikoro peat bogs of the DRC's Congo Basin characterized physico-chemical parameters using digital modeling based on satellite and in situ data. The study found that the pH of the peat bogs varied between 2.600 and 5.000, electrical conductivity measured between 85.48 and 97.99 $\mu\text{S}/\text{cm}$, and the experimental carbon rate was 135.3021 tonnes per hectare. The spatial distribution of the temperature of these peatlands indicated that it ranges between 22.39 and 24.79°C. The results showed that the peat bogs are wetlands that are both significantly acidic and carbon sinks.

Rock-Eval pyrolysis provides a particularly powerful approach for assessing peat degradation. The immature organic matter index (I-index) and refractory organic matter index (R-index) derived from Rock-Eval pyrolysis can distinguish between relatively undecomposed peat and decomposed peat. The I-index represents the proportion of immature organic matter, while the R-index represents refractory organic matter. Disturbed sites typically show lower I-index values and higher R-index values, indicating enhanced decomposition.

3. RESEARCH QUESTIONS

This study is guided by the following research questions:

1. What are the key hydrological and ecological indicators of peatland vulnerability applicable to tropical watersheds, and how do these indicators relate to carbon storage and degradation processes?
2. How can remote sensing and biogeochemical approaches be integrated for monitoring peatland condition and vulnerability across large spatial scales?
3. What are the strengths and limitations of different indicators for assessing vulnerability in the DRC's Cuvette Centrale peatlands?
4. How can multi-scalar indicator frameworks inform conservation and management strategies for tropical peatlands?

4. METHODOLOGY

This study employs a qualitative research design to examine the integration of hydrological and ecological indicators for assessing peatland vulnerability in tropical watersheds.

4.1 Research Design

A systematic review and synthesis approach is adopted, drawing on recent scientific research in remote sensing, biogeochemistry, and hydrological modelling. The research design integrates findings from multiple studies to develop a comprehensive framework for monitoring peatland vulnerability.

4.2 Data Collection

Data were collected through:

Document Analysis: A comprehensive review was conducted of peer-reviewed scientific literature, including studies on remote sensing of peatlands, biogeochemical approaches, and hydrological modelling. Key sources included the Crezee doctoral research, Georgiou's thesis on inundation dynamics, Brown and colleagues' remote sensing research, and hydrological modelling studies.

Secondary Source Review: The study draws extensively on secondary data from institutional research reports, international assessment documents, and conference proceedings.

4.3 Data Analysis

Data were analyzed using thematic analysis. The researcher systematically coded the collected materials to identify recurring patterns and themes related to the research questions. Themes were organized around the categories of hydrological indicators, biogeochemical indicators, remote sensing indicators, and anthropogenic indicators.

4.4 Limitations

As a desk-based study, this research relies on publicly available information and does not include primary data collection through field surveys or direct observation. The analysis synthesizes existing research rather than generating new empirical data.

5. RESULTS

The analysis of documentary and scientific sources reveals a comprehensive framework of indicators for assessing peatland vulnerability in tropical watersheds.

5.1 Hydrological Indicators of Vulnerability

Hydrological indicators provide critical information on the water balance and inundation dynamics that control peatland carbon storage and greenhouse gas emissions.

Inundation Extent and Dynamics: Inundation dynamics constitute the primary control on greenhouse gas emissions from peatlands. Research on the Cuvette Centrale has demonstrated that daily water level maps at 100 m spatial resolution can be achieved using ALOS-2 PALSAR-2 remotely sensed radar data calibrated against field measurements. These maps can categorise locations as rainfed versus those receiving additional water inputs from river flooding, with most rainfed peatlands existing to the west of the Congo River.

Water Table Depth: Groundwater level dynamics in tropical peatlands control geomorphology, ecology, and biogeochemical cycles. Seasonal and interannual water table variations are influenced by rainfall and, in river-influenced systems, by river dynamics. Research has shown that in dry conditions when groundwater levels are deeper than 1 m below soil surface, fire disasters become unavoidable.

Baseflow: Base flow, a steady discharge originating from natural storage, serves as an indicator of the availability and sustainability of river water and is influenced by land cover along the watershed. Changes in land use and cover have a significant impact on hydrological processes. Restoration efforts, such as canal blocking, have been shown to increase base flow and improve water retention.

Evapotranspiration: Evapotranspiration represents the dominant water loss from tropical peatlands, accounting for 62-98% of annual rainfall across different land-cover types . Conversion from peat swamp forest to managed areas causes lower evapotranspiration and higher runoff, altering the hydrological balance.

5.2 Biogeochemical Indicators of Vulnerability

Biogeochemical indicators provide detailed information on peat condition, carbon storage, and degradation processes.

Carbon Density: Peat carbon density provides a direct measure of carbon storage. In the central Congo Basin, the mean carbon density is $1,712 \pm 634$ Mg C per hectare, with a maximum of 3,970 Mg C per hectare. Carbon density varies significantly between regions, with Équateur Province holding the highest density and carbon stock.

Rock-Eval Pyrolysis Indices: The immature organic matter index (I-index) and refractory organic matter index (R-index) derived from Rock-Eval pyrolysis can distinguish between relatively undecomposed and decomposed peat. Disturbed sites typically show lower I-index values (average range in upper section 0.15 to -0.06) and higher R-index values (average range in upper section 0.51 to 0.65) compared to undisturbed sites, indicating enhanced decomposition of the surface peat.

Nutrient Status: Peat nutrient status, indicated by parameters such as the Ca/Mg ratio, provides information on the hydrological and geochemical setting of peatlands. River-influenced peatlands in the DRC are extremely nutrient-poor, with a mean Ca/Mg ratio of surface peat samples of 1.76 ± 0.74 . This low nutrient status explains why peat can form in river-influenced settings, as the peatlands do not classify as minerotrophic.

pH and Electrical Conductivity: Physico-chemical parameters such as pH and electrical conductivity provide information on peatland condition. Research in the Bikoro peat bogs found pH values varying between 2.600 and 5.000, and electrical conductivity between 85.48 and 97.99 $\mu\text{S}/\text{cm}$. These parameters reflect the acidic, nutrient-poor conditions characteristic of tropical peatlands.

Table 1: Vulnerability Indicators for Tropical Peatlands

Indicator Category	Specific Indicator	Application	Key Findings
Hydrological	Inundation extent/dynamics	Primary control on GHG emissions	Daily 100m maps achievable with SAR data
Hydrological	Water table depth	Fire risk; carbon storage	<1m depth indicates fire risk
Hydrological	Baseflow	Water availability; restoration impact	Restored areas show larger baseflow
Biogeochemical	Carbon density	Carbon storage assessment	$1,712 \pm 634$ Mg C/ha average
Biogeochemical	I-index/R-index (Rock-Eval)	Decomposition assessment	Disturbed sites show lower I-index, higher R-index

Biogeochemical	Ca/Mg ratio	Nutrient status; hydrology	River-influenced peatlands: 1.76 ± 0.74
Remote Sensing	Normalized Burn Ratio (NBR)	Degradation detection	Correlates with carbon stocks ($\rho = -0.664$, $p < 0.05$)
Remote Sensing	Radar backscatter	Water level estimation	Relationship with water table depth
Anthropogenic	Deforestation rate	Pressure indicator	>1 million ha/year in DRC
Anthropogenic	Protected area status	Vulnerability indicator	Only 8% of peat carbon protected
Anthropogenic	Concession overlap	Pressure indicator	26% in logging/mining/oil palm concessions

5.3 Remote Sensing Indicators

Remote sensing provides the capacity to monitor peatland condition across large spatial scales.

Normalized Burn Ratio (NBR): The Normalized Burn Ratio (NBR), a satellite-derived parameter, shows significant correlation with peat carbon stocks and decomposition status. Research found that in the top 50 cm section of the peat profile, carbon stocks were negatively related to NBR (Spearman's $\rho = -0.664$, $S = 366$, $p\text{-value} = <0.05$), while there was a positive relationship between the hydrogen index and NBR (Spearman's $\rho = 0.7$, $S = 66$, $p\text{-value} = <0.05$). This suggests that NBR can be used to identify degraded peatland areas and support identification of areas for conservation and restoration.

Radar Remote Sensing: ALOS-2 PALSAR-2 radar data can be used to assess the spatial and temporal dynamics of inundation across the Cuvette Centrale. By determining the relationship between water level and radar backscatter using field collected measurements of water table depth, daily water level maps at 100 m spatial resolution can be produced.

SMOS L-band Data: Assimilation of SMOS L-band brightness temperature observations into land surface models enhances the accuracy of water level estimates. Research has shown improved temporal correlations with in situ data following data assimilation, with state updates showing widespread systematic patterns linked to observed but unmodeled upstream river stage anomalies.

5.4 Anthropogenic Indicators

Anthropogenic indicators provide information on the pressures driving peatland degradation.

Deforestation Rate: Deforestation in the DRC has risen to over 1 million hectares per year in the last 25 years. In the Cuvette Centrale, deforestation is driven by population growth, poor land management, unclear land tenure systems, and the spread of slash-and-burn agriculture.

Protected Area Coverage: Only 8% of central Congo peat carbon lies within national protected areas. This limited coverage leaves the majority of peatlands vulnerable to land-use change. In the DRC, protected area coverage is even lower, with only 7% of peat carbon within national protected areas.

Concession Overlap: Approximately 26% of central Congo peatland area falls within logging, mining, or palm oil concessions. This overlap creates significant pressure on peatland ecosystems. In the DRC, 26% of peatlands are in concessions, compared to 25% in the Republic of Congo.

6. DISCUSSION OF RESULTS

The findings reveal a comprehensive framework of multi-scalar indicators for assessing peatland vulnerability in tropical watersheds. This section discusses the integration of these indicators for monitoring vulnerability and guiding conservation strategies.

6.1 The Role of Inundation Dynamics as a Primary Indicator

Inundation dynamics constitute the primary control on greenhouse gas emissions from peatlands. The ability to map inundation dynamics at daily intervals and 100 m spatial resolution using radar remote sensing provides a powerful tool for understanding peatland vulnerability. The distinction between rainfed and river-influenced peatlands is critical, as these systems have different hydrological sensitivities and vulnerability profiles.

Rainfed peatlands in the western portion of the Cuvette Centrale are sensitive to rainfall variability and are likely to be more vulnerable to drought. River-influenced peatlands in the eastern portion may be more resilient to rainfall variability but are sensitive to changes in river dynamics and upstream land-use change. The research by Apers and colleagues demonstrated the sensitivity of the hydrology of the Congo Basin peatlands to local and upstream rainfall variability, as well as river dynamics, emphasizing the need for integrated hydrological and land management approaches.

6.2 Integration of Remote Sensing and Biogeochemical Approaches

The integration of remote sensing and biogeochemical approaches offers a comprehensive framework for monitoring peatland condition and vulnerability. The research by Brown and colleagues demonstrated that the Normalized Burn Ratio (NBR) correlates significantly with peat carbon stocks and decomposition status. This finding is significant because it provides a method for identifying degraded peatland areas across large spatial scales using satellite data.

The combination of remote sensing with biogeochemical analysis offers several advantages. Remote sensing provides spatial coverage but limited information on degradation processes. Biogeochemical analysis provides detailed information on decomposition and carbon dynamics but is limited to point samples. By combining these approaches, it is possible to identify priority areas for conservation and restoration and to track the effectiveness of management interventions.

6.3 Multi-Scalar Indicator Frameworks

The identification of four categories of vulnerability indicators hydrological, biogeochemical, remote sensing, and anthropogenic provides a comprehensive framework for assessing peatland vulnerability. Each category offers different strengths and limitations.

Hydrological indicators provide direct information on the water balance and inundation dynamics that control peatland carbon storage. However, they require field measurements or sophisticated modelling to be useful. Biogeochemical indicators provide detailed information on peat condition and degradation but are limited to point samples. Remote sensing indicators offer spatial coverage but may not capture all aspects of peatland condition. Anthropogenic indicators provide information on the pressures driving degradation but do not directly measure peatland condition.

Integrating these indicators at multiple scales is essential for developing effective conservation strategies. The PIREDD Mongala programme, which aims to reduce deforestation and promote sustainable land use, demonstrates the importance of addressing anthropogenic pressures while monitoring ecological condition. The DRC's national peatland strategy provides a framework for policy integration.

6.4 Vulnerability Thresholds and Resilience

The research suggests that tropical peatlands may be approaching critical thresholds where combined climatic and anthropogenic pressures could trigger large-scale carbon release. The paleoenvironmental research demonstrating that the Cuvette Centrale peatlands are vulnerable to climatic drying indicates that these systems may lie close to a climatically driven drought threshold.

The findings from Southeast Asian peatlands provide insights into potential responses. Research has shown that in dry conditions when groundwater levels are deeper than 1 m below soil surface, fire disasters are unavoidable. When areas susceptible to fire burn, the total inundated area will expand. This suggests that tropical peatlands can experience rapid and potentially irreversible changes when critical thresholds are crossed.

6.5 Implications for Conservation and Management

The findings have several implications for conservation and management of tropical peatlands in the DRC. First, the development of a comprehensive monitoring framework incorporating hydrological, biogeochemical, remote sensing, and anthropogenic indicators is essential for tracking peatland condition and identifying priority areas for intervention. Second, the integration of remote sensing and biogeochemical approaches offers a practical method for assessing peatland degradation across large spatial scales. Third, the vulnerability of peatlands to climatic drying and anthropogenic pressures underscores the need for integrated management approaches that address both pressures simultaneously. Fourth, the limited protected area coverage and extensive concession overlap in the DRC highlight the need for enhanced governance and enforcement.

7. CONCLUSION

This study has examined the integration of hydrological and ecological indicators for assessing peatland vulnerability in tropical watersheds, synthesizing remote sensing, biogeochemical, and hydrological modelling approaches applicable to the DRC's Cuvette Centrale peatlands. The findings reveal a comprehensive framework of multi-scalar indicators for monitoring peatland condition and vulnerability.

The analysis identifies four categories of vulnerability indicators applicable to DRC's watersheds. Hydrological indicators, including inundation dynamics, water table depth, and baseflow, provide direct information on the water

balance that controls peatland carbon storage. Biogeochemical indicators, including carbon density, Rock-Eval pyrolysis indices (I-index and R-index), and nutrient status, provide detailed information on peat condition and degradation processes. Remote sensing indicators, including the Normalized Burn Ratio (NBR) and radar backscatter, offer the capacity to monitor peatland condition across large spatial scales. Anthropogenic indicators, including deforestation rate, protected area status, and concession overlap, provide information on the pressures driving degradation.

The integration of these indicators at multiple scales offers a comprehensive framework for assessing peatland vulnerability and guiding conservation strategies. The finding that the Normalized Burn Ratio (NBR) correlates significantly with peat carbon stocks and decomposition status (Spearman's $\rho = -0.664$, $p < 0.05$) provides a practical method for identifying degraded peatland areas across large spatial scales. The ability to map inundation dynamics at daily intervals and 100 m spatial resolution using radar remote sensing offers a powerful tool for understanding the primary control on greenhouse gas emissions from peatlands.

The path forward requires sustained investment in monitoring infrastructure and capacity building. The Cong'eaux project, which aims to advance understanding of spatiotemporal ecohydrological variability in the Congo Basin, and the ORACLE project, which has provided important insights into past climate-peatland interactions, represent important steps toward addressing knowledge gaps. However, much work remains. As the 2025 Congo Basin Assessment Report emphasizes, enhanced investments in science, governance, and regional resilience are essential to safeguard these ecosystems against intensifying climatic and anthropogenic pressures.

8. LIMITS OF THE STUDY

This study is subject to several limitations that should be acknowledged. First, the research is primarily desk-based, relying on publicly available documents and secondary sources. The absence of primary data collection through field surveys means that the analysis synthesizes existing research rather than generating new empirical data. Second, the availability of scientific data specific to the DRC's Cuvette Centrale is limited, particularly for biogeochemical analysis and hydrological modelling. Much of the analysis relies on extrapolation from research conducted elsewhere, particularly in Southeast Asia. Third, the rapidly changing nature of the security and political context in the DRC means that some findings may become outdated. Fourth, the study does not include quantitative modelling of future climate impacts or land-use change scenarios.

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10. AUTHOR CONTRIBUTIONS

The author was responsible for the entire research and writing process, including conceptualization, design, literature review, data collection and analysis, and drafting, reviewing, and editing the final manuscript.

11. COMPETING INTEREST

The author declares no competing interests. No personal or financial relationships exist that could have inappropriately influenced the writing of this article.

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13. DATA AVAILABILITY

All data used in this analysis are derived from publicly available sources, including peer-reviewed academic publications, institutional research reports, and international assessment documents. All sources are cited in the bibliography.

14. DISCLAIMER

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