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An Aggregate Vulnerability Index for Addressing Climate Change in the Congo Basin: Methodology and Application

[Indice agrégé de vulnérabilité due au changement climatique dans le bassin du Congo : Méthodologie et application]

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Abstract

Vulnerability to climate change, a long-standing focus of scientific research and policy discussions, has become more complex as traditional methods of quantifying vulnerability face significant uncertainties. These uncertainties arise from the complex and evolving nature of climate systems, which involve interactions that are often difficult to measure. This study aims to understand and quantify the vulnerability of ecosystems in the Congo Basin to climate change by developing an Aggregate Vulnerability Index for addressing Climate Change (AVICC). The AVICC uses a holistic methodology that combines both quantitative and qualitative approaches to assess the exposure of the system to climate drivers, the sensitivity of the system particularly to land cover change and its adaptive capacity in terms of socio-economic and institutional factors. This approach includes the analysis of vulnerability indices, their standardisation and aggregation, which allows the quantification of this multidimensional vulnerability and supports the prioritisation of adaptation measures. The case study, which applies the AVICC to the climate-water-migration-conflict nexus in the northeastern Congo Basin, shows that limited adaptive capacity in the Aruwimi, Itimbiri and Uele catchments exacerbates vulnerability to climate change. Socio-economic challenges such as food insecurity, water scarcity, gender inequality and conflicts driven by migration and resource scarcity contribute significantly to this vulnerability. The AVICC provides a comprehensive tool for assessing vulnerability and facilitates the design of targeted adaptation strategies that address environmental, socio-economic and institutional issues related to climate change, thereby in-creasing the resilience of communities and ecosystems to future climate challenges.

Keywords: Climate change vulnerability, Aggregate Vulnerability Index, climate–water–migration–conflict nexus, adaptation strategies, Congo Basin.

Résumé

La vulnérabilité au changement climatique, sujet de longue date des recherches scientifiques et des débats politiques, s'est complexifiée à mesure que les méthodes traditionnelles de quantification de cette vulnérabilité rencontrent d'importantes incertitudes. Ces incertitudes découlent de la nature complexe et évolutive des systèmes climatiques, caractérisés par des interactions souvent difficiles à mesurer. Cette étude vise à comprendre et quantifier la vulnérabilité des écosystèmes du bassin du Congo face au changement climatique, en développant un Indice Agrégé de Vulnérabilité au Changement Climatique (IAVCC). L'IAVCC utilise une méthodologie holistique combinant des approches quantitatives et qualitatives pour évaluer l'exposition du système aux facteurs climatiques, la sensibilité du système notamment aux changements d'occupation des sols, ainsi que sa capacité d'adaptation en tenant compte des facteurs socio-économiques et institutionnels. Cette approche comprend l'analyse des indices de vulnérabilité, leur standardi-sation et leur agrégation, permettant ainsi de quantifier cette vulnérabilité multidimensionnelle et d'orienter la hiérarchisation des mesures d'adaptation. L'étude de cas, qui applique l'IAVCC au nexus climat-eau-migration-conflit dans le nord-est du bassin du Congo, révèle que la capacité d'adaptation limitée dans les bassins versants de l'Aruwimi, de l'Itimbiri et de l'Uele accentue la vulnérabilité au changement climatique. Des défis socio-économiques tels que l'insécurité alimentaire, la rareté de l'eau, les inégalités de genre et les conflits liés à la migration et à la rareté des ressources contribuent de manière significative à cette vulnérabilité. L'IAVCC constitue un outil complet pour évaluer la vulnérabilité et facilite l'élaboration de stratégies d'adaptation ciblées, abordant les enjeux environnementaux, socio-économiques et institutionnels liés au changement climatique, renforçant ainsi la résilience des communautés et des écosystèmes face aux défis climatiques futurs.

Mots-clés : Vulnérabilité au changement climatique, indice agrégé de vulnérabilité, nexus climat–eau–migration–conflit, stratégies d'adaptation, bassin du Congo.

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1. Introduction

The effects of climate change are increasingly being felt around the world, with adverse impacts on the environment and related socio-economic sectors. At high levels of warming, climate impacts are observed on biodiversity and eco-system services, agricultural activities and food security, human and animal health, water resource availability and systems, human migration and conflict, etc. (Intergovernmental Panel on Climate Change [IPCC], 2022; Tshimanga et al., 2022). Social and economic systems are unlikely to be spared as the effects of climate change intensify. As the effects of climate change intensify and social and economic systems are unlikely to be spared (Ludena & Won, 2015; Merkenschlager et al., 2023; IPCC, 2017).

Climate models are unanimous in warning policy-makers and populations of the immediate impact of climate uncertainty on the socio-economic life of communities. African countries such as the Democratic Republic of Congo (DRC) and other countries in the Congo Basin, long thought to be immune to the effects of climate change, are currently subject to major climate related uncertainties, including poor rainfall patterns, long dry seasons, extreme events, etc., and are therefore vulnerable (Laraque, et al., 2020; Tshimanga et al., 2021; 2022). The effects of climate change manifest themselves in agriculture and food security, human and animal health, livelihoods and food security, for example when women have to travel long distances to fetch water (Malone & Brenkert, 2009; Nelleman et al., 2011; Wheeler, 2011; Faye and Ndong, 2015) These effects increase the vulnerability of the 120 million people living in the Congo Basin, who depend mainly on rainfed agriculture (IPCC, 2022).

The interlinkages between climate change, water resources, livelihoods and other socioeconomic factors are highly intricate and dynamic, involving complex interactions that make it challenging to analyse each factor in isolation (Bar-nett and Adger, 2007; Adger et al., 2011; Gemenne et al., 2014). These elements intersect, intertwine, and mutually influence one another, creating a network of interdependencies that defies simple evaluation (Tshimanga et al., 2022). Consequently, assessing vulnerability within this multifaceted system is essential for enhancing the resilience of communities and the ecosystems they rely on.

Reducing vulnerability to the adverse effects of climate change through adaptation and resilience-building has been a global priority since the Paris Agreement (United Nations, 2015), and it remained a central focus at the COP 26 in Glasgow (United Nations Framework Convention on Climate Change [UNFCCC], 2021), emphasizing its importance for community well-being, sustainable development, and ecosystem preservation (Tshimanga et al., 2022). Vulnerability assessment is critical for integrating assessments of climate change impacts into ongoing planning for adaptation strategies and resilient development (Pavageau et al., 2013).

Over the past decades, vulnerability assessment methodologies have evolved in fields such as natural hazards, food security, poverty analysis and sustainable livelihoods (Deutsche Gesellschaft für Internationale Zusammenarbeit [GIZ], 2017). In the Congo Basin, however, many approaches still rely on traditional methods, which are often constrained by uncertainties in climate projections and evolving socioeconomic dynamics (Hossain, 2001; Fekete, 2009; Pavageau et al., 2013; International Monetary Fund [IMF], 2022; Karam, et al., 2022). To be effective, vulnerability assessments need to take a holistic approach, encompassing not only the physical dimensions of climate change, but also the socio-economic and institutional factors that shape its impacts. These multidimensional influences highlight the complexity of accurately assessing and addressing vulnerability to climate change (Observatoire National sur les Effets du Réchauffement Climatique [ONERC], 2005; Pavageau et al., 2013; Kerstin et al., 2016; IPCC, 2022).

Recent studies suggest that using indicator and index-based approaches for vulnerability assessment can offer a rapid and insightful understanding of complex phenomena (Feitelson & Chenoweth, 2002; Eriksen & Kelly, 2006; GIZ, 2017; Xu, et al., 2020). These indices enable comparison across different timeframes and regions, helping to reveal hidden heterogeneities at finer scales and pinpointing the most vulnerable areas (Sullivan, 2005).

Balica (2012) categorizes vulnerability indices into three types: aggregate, less aggregate, and simple indices. Aggregate indices synthesize various vulnerability parameters into a single value, such as the Watershed Sustainability Index (WSI), which integrates hydrological, environmental, and socio-political factors into a dynamic, quantitative measure (Chaves & Alipaz, 2007). Less aggregated indices, like the Climatic Moisture Index (CMI) (Vörösmarty, 2005), the Standardised Precipitation Index (SPI) (Giddings et al., 2005), the Standardised Precipitation and Evapotranspiration Index (SPEI) (Vicente-

Serrano, 2010) and the Effective Drought Index (EDI) (Byun & Wilhite, 1999), have been used to assess climate change vulnerability by focusing on specific climate variables. Simple indices, often measurable variables, can also contribute to overall assessments or provide a standalone picture of vulnerability, such as irrigated land percentage or under five mortality rates. These indices, whether aggregate or simple, offer critical tools for assessing and responding to vulnerability in the face of climate change (Leichenko & O'brien, 2002).

In light of the current and future challenges posed by climate change, it is imperative to develop an aggregate vulnerability index that considers the ecological, social, and economic dimensions of the Congo Basin. As an objective tool, it would inform policy-makers in designing targeted climate adaptation strategies and improving the livelihoods of vulnerable communities. By aggregating different indices of vulnerability, this index could help to identify priority areas for intervention, facilitate the allocation of resources and enhance the resilience of affected populations (Organisation de Coopération et de Développement Économiques [OCDE], 2013). In this context, the paper introduces the develop-ment of the Aggregate Vulnerability Index for Climate Change (AVICC) in the Congo Basin and presents a case study that assesses vulnerability linked to the climate-water-migration conflict nexus in the northeastern catchments of the region namely Uele, Aruwimi and Itimbiri.

Uele (139 124 Km2), Aruwimi (120 406 Km2), and Itimbiri (52 854 Km2) constitute significant catchments in the north-eastern part of the Congo Basin, contributing to local and regional water security through the diverse goods and services they provide (Tshimanga and Hugues, 2012; Trigg and Tshimanga, 2020). The Uele, Aruwimi and Itimbiri catchments encompass three provinces of the DRC, respectively the province of Haut-Uele (89,683 km2; 1,826,974 in-habitants), the province of Ituri (65,658 km2; 3 875 113 inhabitants) and the province of Bas-Uele (148,331 km2; 1 212 047 inhabitants) (Omasombo, 2011, 2014; Tshimanga, et al., 2021). These catchments are bordered (figure 1) to the north by the Central African Republic and South Sudan, to the south by the provinces of Tshopo and North Kivu in DRC, to the east by Uganda and to the west by the provinces of Mongala and North Ubangi in DRC (Tshimanga, et al., 2021).

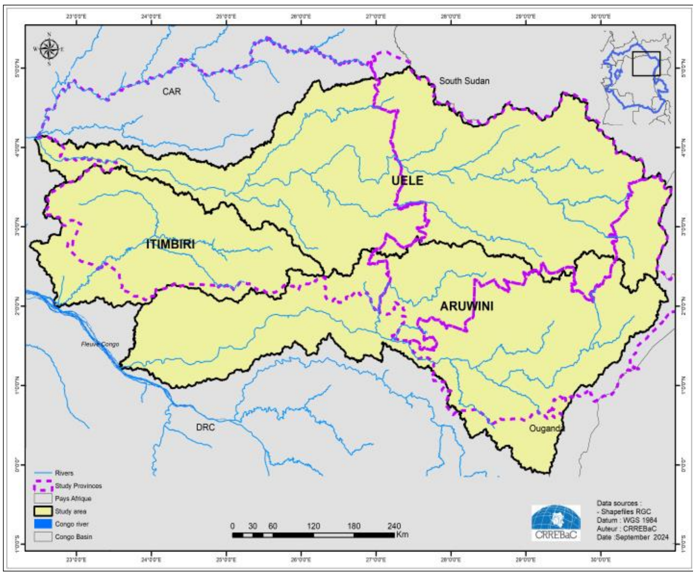


Figure 1. Map of the Uele, Itimbiri and Aruwimi catchments located within the north-eastern part of the Congo

This region is recognised as a hotspot for various critical issues (Tshimanga, et al., 2021), including the impact of climate change on agricultural production and livestock farming (Karam, et al., 2022; FSIN and Global Network Against Food Crises, 2023), the difficulties of access to food and water (United Nations Environment Programme [UNEP], 2011), the institutional capacity constraints and the lack of technologies to enhance community livelihoods (UNEP, 2011), alarming rates of deforestation and degradation of natural resources (Atyi, 2022), outbreaks of epidemics such as cholera and Ebola, conflicts linked to pastoral migration (African Union, 2008; Kabamba, 2015; Dialogue des Peuples, 2016; Furlow, 2022), which exacerbate the presence of multiple politico-military activities (Kabamba, 2015), with women and girls being the most affected (Tshimanga, et al., 2022). Figure 2 presents a causal loop diagram which illustrates the dynamics and complexity of the factors related to the vulnerability due to the climate water migration conflict nexus in the north-eastern part of the Congo Basin. These factors and their root causes are adversely affecting the ecosystem and the vulnerable populations living in the area. In this complex and multifaceted context, there is an urgent need to develop an AVICC that addresses the challenges posed by the climate water migration conflict nexus. Such an index would serve to identify adaptation priorities and ultimately en-hance the resilience of affected communities.

The exposure factors encompass a range of climatic variables, including temperature, precipitation, evapotranspiration.

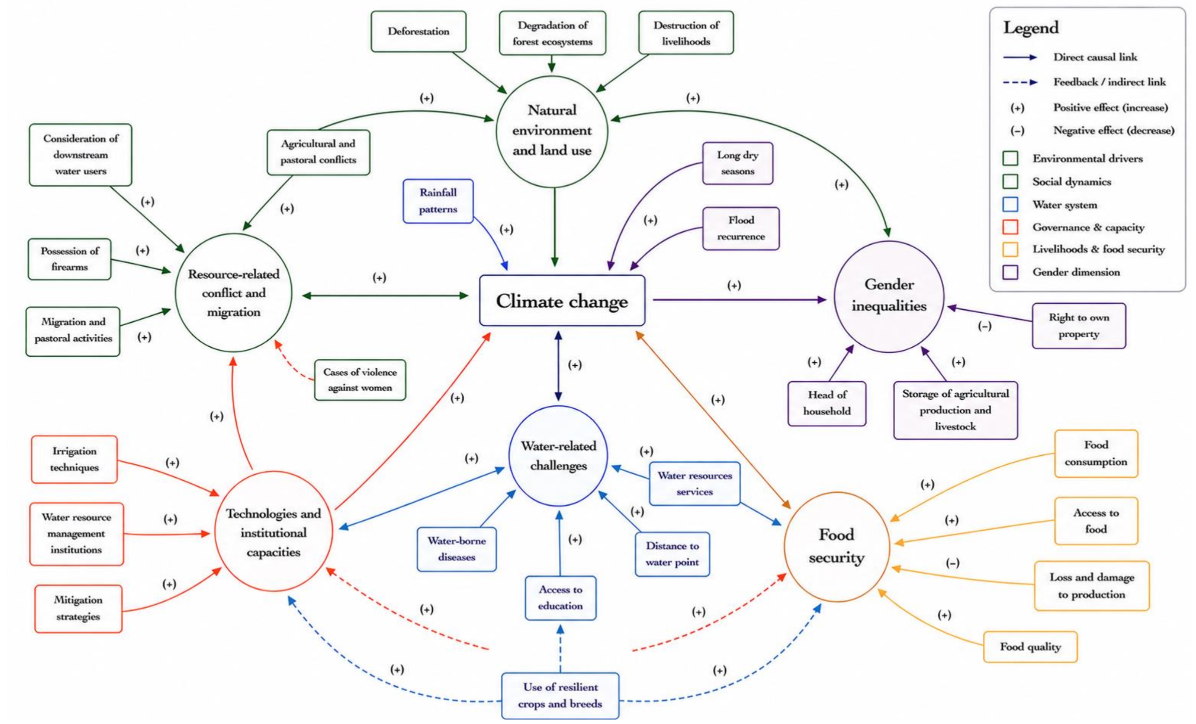


Figure 2. Causal loop diagram to describe the dynamics and complexity of factors related to the cli-mate-water-migration-conflict nexus in the north-eastern part of the Congo Basin.

2. Material and methods

2.1. Conceptual framework

The vulnerability of a system to climate change depends on the nature, magnitude and rate of climate change to which the system is exposed, as well as its sensitivity and adaptive capacity (Parry et al., 2007). From this definition, three key factors can be identified that determine whether, and to what extent, a system is likely to be impacted by climate change: exposure, sensitivity and adaptive capacity. Another related concept, known as impact potential, also contributes to the definition of vulnerability. However, unlike the other three factors, it is not a vulnerability factor in itself, but results from the interaction between exposure and sensitivity. The different concepts derived from this definition of vulnerability to climate change are described below.

- Exposure: is the only factor that is directly influenced by hydro-climatic parameters, specifically the nature, magnitude, and rate of climate change and variability.

The climatic water balance, and extreme events such as floods and meteorological or hydrological droughts (Parry et al., 2007; Global Water Partnership [GWP] & World Meteorological Organization [WMO], 2016).

- Sensitivity: determines the degree to which a system is positively or negatively affected by a given exposure to climate change. The degree of sensitivity of a system is typically contingent upon the intrinsic characteristics of the natural and/or physical environment, including topography, the capacity of different soil types to resist erosion, and the type of land cover (Parry et al., 2007; UNFCCC, 2010).

- Adaptive capacity: is defined as a set of factors that determine the ability of a system to generate and implement adaptation measures. Factors related to the capacity for adaptation are closely associated with the re-sources available within human systems, as well as their socio-economic, structural, institutional and technical characteristics and capabilities (Parry et al., 2007).

- Potential impact: The potential impact of climate change is determined by the combination of exposure and sensitivity. The effects of climate change can result in a chain of impacts that extend from the biophysical sphere to the social sphere, with varying degrees of intensity (Parry et al., 2007).

Figure 3 illustrates the conceptual framework proposed in this study to develop the Aggregate Vulnerability Index for addressing Climate change (AVICC) in the Congo Basin.

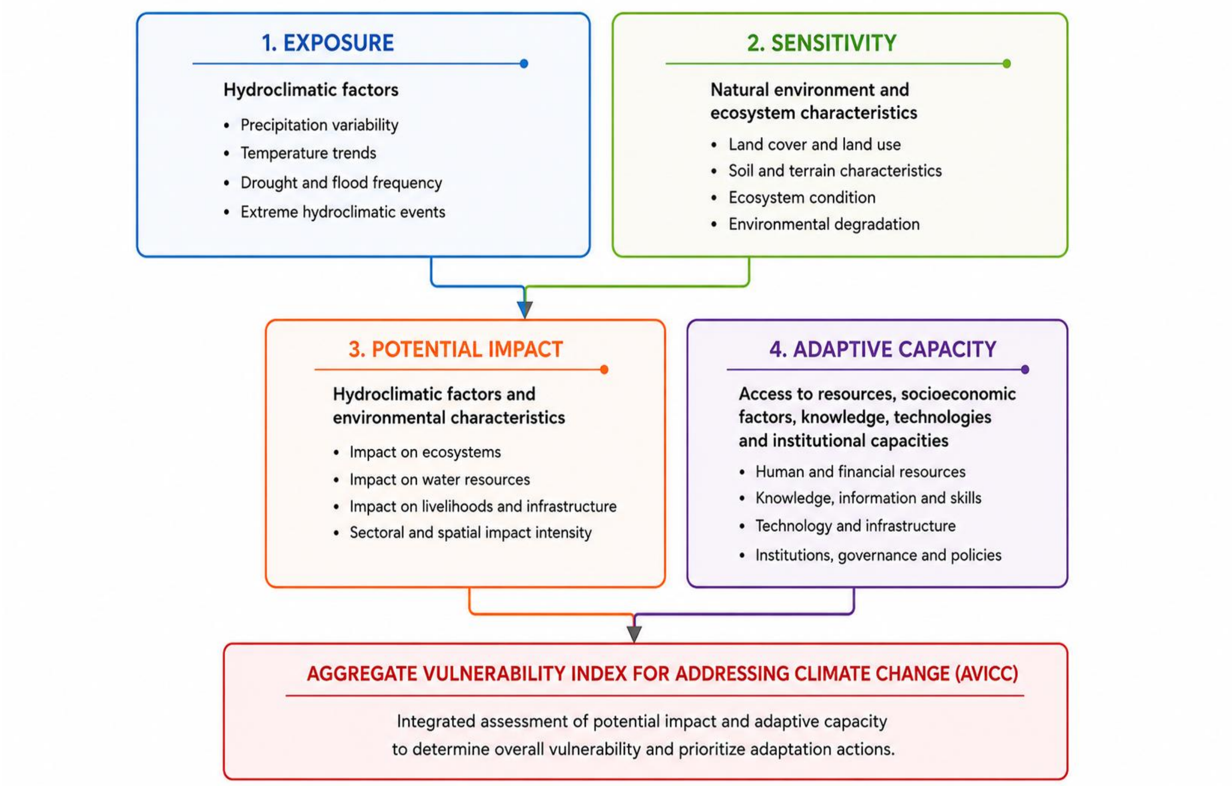


Figure 3. Conceptual framework to illustrate the approach for the development of the AVICC in the Congo Basin

2.2. Methodological approach

To develop an aggregate index of vulnerability to climate change in the Congo Basin, we propose a holistic methodology that integrates both quantitative and qualitative approaches, given the multidisciplinary nature of climate change. The quantitative approach may entail the analysis of available data related to land cover maps and time series of hydro-climatic variables, derived from climate modelling. The qualitative approach typically involves an analysis of so-cio-economic survey data. The methodology involves an analysis of vulnerability indices, their standardisation and aggregation (Parry et al., 2007; IPCC, 2007; 2022).

2.2.1. Analysis of vulnerability indices Climate change vulnerability indices are defined as measures used to assess, compare or monitor the degree of vulnerability of a system, community or ecosystem to the impacts of climate change. The indices take into account different vulnerability factors presented. These indices are related to the climatic, biophysical and socioeconomic parameters.

The indices can be analysed using the available data and according to the specific methodologies. the assessment. Table I lists the types of indices per vulnerability factor that can be used in the development of the AVICC.

Table I. Types of indices per vulnerability factor that can be used in the development of the AVICC

Vulnerability factor	Description/Examples
Exposure	These indices measure deviations from normal climatic or hydrological conditions and help detect exposure to drought. Key examples include: Standardized Precipitation and Evapotranspiration Index (SPEI), Abnormal Aridity Index (AAI), Weighted Anomaly of Standardized Precipitation (WASP), Aridity Index (AI), Drought Area Index (DAI), Climatic Moisture Index (CMI), Drought Detection Index (DDI), Palmer Z Index, NOAA Drought Index (NDI), Evapotranspiration Deficit Index (ETDI), Palmer Hydrological Drought Index (PHDI), Standardized Reservoir Storage Index (SRSI), Surface Water Supply Index (SWSI), etc.
Sensitivity	These indices reflect how ecosystems or natural resources respond to climatic stress. Examples include: Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Land Surface Water Index (LSWI), Vegetation Condition Index (VCI), Vegetation Response to Drought Index (VEGRI), Vegetation Health Index (VHI), Soil-Adjusted Vegetation Index (SAVI) and Water Requirement Index (WRI)
Adaptive Capacity	These indices reflect the ability of communities or systems to adapt and respond to climate stress. Examples include: Food Access Insecurity Index (FAI), Poor Food Consumption (PFC), Poor Diet Quality (LDQ), Internal Armed Conflict Index (CAI), Water Accessibility Index (WAI), Human Development Index (HDI), Gender Inequality Index (GII) and others classic socioeconomic and governance indices

2.2.2. Standardisation of indices

Standardisation is the transformation of index values assessed on different scales and using different units of measurement into unitless values on a common scale (OCDE, 2017; Becker et al., 2017). Calculated vulnerability indices need to be standardised before being aggregated. Standardisation of indices involves assigning meaning to numbers by assessing at what value an index becomes critical; "0" is defined as "optimal situation, no improvement is necessary or possible" and "1" as "critical situation, the system is no longer functioning". A low score corresponds to a "low" value and a high score to a "high" value in terms of vulnerability. The minimum-maximum method was used to standardise the indices, according to the following equation:

$$\mathbf{Xi\ 0\ to\ 1} = \frac{\boldsymbol{Xi - Xmin}}{\boldsymbol{X\,max - Xmin}}$$

Where Xi 0 to 1 represents the standardised value within the field from 0 to 1; Xi represents the value of the individual data to be standardised; X min represents lowest value of the index; and X max represents the highest value of the index.

2.2.3. Aggregation of indices

Aggregation is a process of combining data from different indices into a composite index that represents vulnerability as a single factor. The weighted arithmetic aggregation method is recommended for aggregating indices to avoid distortionary effects when distortionary effects when aggregating several factors. The choice of weights can significantly affect the outcomes. It is essential to base these on empirical data or expert judgment to reflect true importance accurately (Parry, 2007; OCDE, 2008, 2013, 2017). This is a common, simple and transparent method of aggregation. The aggregation of indices is done in three steps:

- Aggregation of indices of the same vulnerability factor;
- Aggregation of exposure and sensitivity into potential impact;
- Aggregation of potential impact and adaptive capacity into an aggregate vulnerability index.

2.2.4. Aggregation of component indices

To establish the representative index for a vulnerability factor, the individual indices are multiplied by their weights, added together and divided by the sum of all their values. The formula below summarises this method.

$$\mathbf{Ic} = \frac{\boldsymbol{I1} * \mathbf{C1} + \boldsymbol{I2} * \mathbf{C2} + \cdots \boldsymbol{In} * \mathbf{Cn}}{\boldsymbol{\Sigma}\mathbf{C}}$$

Where Ic represents the composite index representative of a vulnerability factor; I represent the individual index of a vulnerability factor; C represents the weighting coefficient assigned to the index; and n: nth index or coefficient.

After calculating the representative index of two factors of vulnerability, exposure and sensitivity, these two factors must be combined to form the subsidiary component of vulnerability called "potential impact". The weighted arithmetic aggregation method is again applied to calculate the composite potential impact index. The formula is as follows:

$$\mathbf{PI} = \frac{\boldsymbol{EX} * \mathbf{CEX} + \boldsymbol{SE} * \mathbf{CSE}}{\mathbf{CEX} + \mathbf{CSE}}$$

Where PI represents the composite index of potential impact; EX represents the exposure; SE represents the Sensitivity; and C represents the weighting coefficient assigned to the factor.

2.3. Data used and analysis

The final step is to integrate the composite index of potential impact with the adaptive capacity, resulting an AVICC. The weighted arithmetic aggregation method is again applied. The formula is presented below:

$$\mathbf{AVICC} = \frac{\mathbf{IP} * \mathbf{CPI} + \mathbf{CA} * \mathbf{CCA}}{\mathbf{CPI} + \mathbf{CCA}}$$

Where AVICC represents the aggregate vulnerability index of climate change; PI represents the composite potential impact index; AC represents the composite adaptive capacity index; C represents the weighting assigned to vulnerability components.

In addition to providing a comprehensive global view of a system's vulnerability to climate change and its associated consequences by aggregating relevant factors, the AVICC offers effective responses to the following key questions: Where are the most vulnerable areas, or what are the issues that require special attention due to their critical situation? What are the main drivers on which adaptation options should be based? What are the various barriers or root causes of increased vulnerability to climate change?

2.3. Data used and analysis

Table II describes the indices used by vulnerability factor, their data source, and the different calculation formulas.

Table II. Indices used by vulnerability factor, data source and different calculation formulas related to the climate-water-migration-conflict nexus

Vulnerability factor	Index	Description
Exposure	**SPEI** *(Standardized Precipitation Evapotranspiration Index)*	Based on the difference between precipitation (P) and potential evapotranspiration (PET). The cumulative (P − PET) value is fitted to a logistic model. Negative values indicate dry conditions, and positive values indicate wet conditions relative to a reference period (Vicente-Serrano, 2010).
Sensitivity	**NDVI** *(Normalized Difference Vegetation Index)*	A normalized spectral index that measures vegetation vigor. It is used to detect land cover changes and assess ecological impacts of climate variability and human activities such as pastoral mobility (Boori et al., 2014; Hamidi et al., 2019).
	FAI *(Food Accessibility Index)*	Measures the percentage of households facing severe food access limitations due to inadequate resources, including income, food prices, market availability, and socio-political conditions (Mbunga et al., 2023).
	PCI *(Poor Food Consumption Index)*	Reflects households regularly consuming insufficient, nutritionally inadequate, and undiversified diets (Coates et al., 2007; Mbunga et al., 2023).
	PDQ *(Poor Diet Quality)*	Indicates nutrient-deficient diets lacking variety and balance, especially in essential food groups like fruits, vegetables, proteins, and micronutrients (Coates et al., 2007; Mbunga et al., 2023).
	NDP *(No Decline in Production)*	Percentage of households maintaining stable agricultural production and food reserves, indicating resilience to shocks such as extreme events or livestock damage (Sullivan & Meigh, 2005; 2021; Tshimanga et al., 2021).
	NSAP *(No Storage of Agricultural Production)*	Households not storing their production due to losses from pests or climate impacts, an indicator of increased food vulnerability (Chambers & Conway, 1992; Scoones, 1998; Etongo & Arrisol, 2021; Tshimanga et al., 2021).
	NRCB *(No Resilient Crops and Breeds)*	Percentage of households not planting resilient crops or breeds, indicating a limited ability to adapt to environmental changes (Botta & Kozluk, 2014; Tshimanga et al., 2021).
	NDWC *(No Downstream Water Consideration)*	Proportion of households not considering downstream users when using water, highlighting overuse and potential water conflicts (Lester & Rhiney, 2018; Tshimanga et al., 2021).

Adaptive Capacity	**COP** *(Conflict on Property)*	Households experiencing armed or unarmed conflict on their property—an indicator of local conflict resolution capacity (SIPRI & NUPI, 2021; Tshimanga et al., 2021).
	DMH *(Displaced or Migrant Households)*	Proportion of households displaced or migrated due to climate or other stressors—a marker of vulnerability to forced mobility (Cambrézy & Lassailly-Jacob, 2010; UNECA, 2012; IOM, 2019; Tshimanga et al., 2021).
	NWHH *(Non-Women-Headed Households)*	Percentage of households not led by women, highlighting structural gender disadvantages such as dependency, limited assets, and lower mobility (Nelleman et al., 2011; Tshimanga et al., 2021, 2022).
	WNAS *(Women in Non-Agricultural Sector)*	Proportion of women employed in non-agricultural sectors, reflecting economic inclusion and empowerment (Nelleman et al., 2011; Tshimanga et al., 2021, 2022).
	NSM *(No Structural Mitigation)*	Households not applying structural mitigation strategies, reflecting weak community-level responses to climate risks (Malone & Brenkert, 2009; Botta & Kozluk, 2014; Tshimanga et al., 2021).
	NAWS *(No Alternative Water Source)*	Proportion of households without access to alternative water sources—an indicator of water access vulnerability (Feitelson & Chenoweth, 2002; Tshimanga et al., 2021).
	NDWA *(No Drinking Water Access)*	Percentage of rural households lacking access to improved drinking water sources (e.g., piped water, protected springs, rainwater) (Feitelson & Chenoweth, 2002; Tshimanga et al., 2021).
	NIS *(No Irrigation System)*	Households not using irrigation systems—indicates reliance on rain-fed agriculture and limited technical capacity (Botta & Kozluk, 2014; Tshimanga et al., 2021).
	NWMO *(No Watershed Management Organisation)*	Absence of local watershed management organizations—critical for sustainable resource use, conflict prevention, food security, and climate adaptation (Tshimanga et al., 2021).

The precipitation and evapotranspiration data used to calculate the 12-month average SPEI from 1990 to 2021 were sourced from the Congo Basin Water Resources Research Centre (CRREBaC), which provided the time series from 1986 to 2020 for the Bambesa Station, complemented by the Watch Forced Era Interim (WFDEI) reanalysis dataset, containing daily data on various climatic factors (Karam, et al., 2022). The spatial data from 1991 to 2020 used to determine land cover with NDVI were obtained from the National Oceanic and Atmospheric Administration (NOAA) (Hamidi et al., 2019). Finally, the socio-economic data related to adaptation capacity come from the Integrated Information System on the Climate-Water-Migration-Conflict nexus in the Congo Basin, developed by CRREBaC (Tshimanga et al., 2021).

3. Results

3.1. Calculated value of vulnerability indices

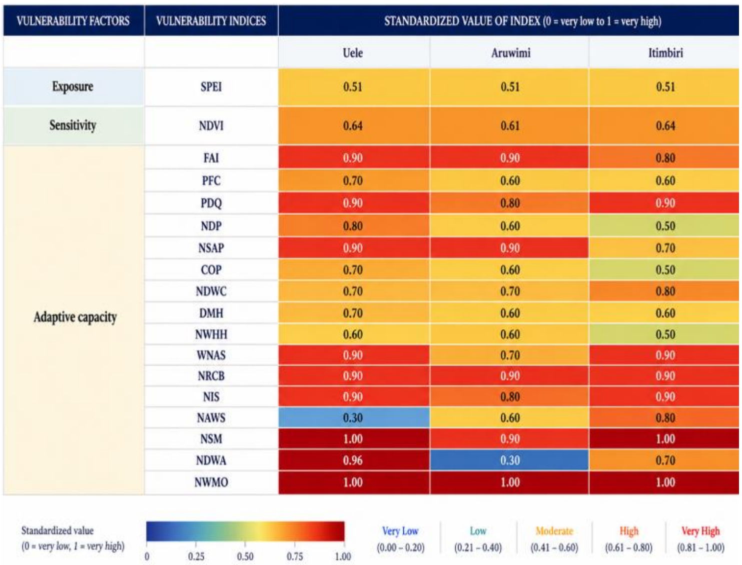
Table III shows the vulnerability index values for three river basins (Uele, Aruwimi, Itimbiri). Drought vulnerability is moderate (SPEI = -0.04) and forest vulnerability is low (NDVI = 0.36-0.37). However, adaptive capacity is critically low due to high food insecurity (FAI up to 0.9), low food consumption (PFC up to 0.7), frequent resource related conflicts and significant migration pressures. Gender inequality, limited technology and weak institutional capacity including lack of watershed management and minimal resilient agriculture exacerbate vulnerability. These communities depend on rain-fed agriculture and lack awareness of downstream water impacts, requiring urgent climate adaptation measures.

Table III. Calculated value of vulnerability indices related to the climate-water-migration-conflict nexus

Vulnerability factors	Vulnerability indices	Measure Scale of Index	Calculated value of index		
			Uele	Aruwimi	Itimbiri
Exposure	SPEI	-2 to 2	-0.04	-0.04	-0.04
Sensitivity	NDVI	-0.28 to 0.74	0.37	0.37	0.36
Adaptive capacity	FAI	0 to 1	0.9	0.9	0.8
	PFC		0.7	0.6	0.6
	PDQ		0.9	0.8	0.9
	NDP		0.8	0.6	0.5
	NSAP		0.9	0.9	0.7
	COP		0.7	0.6	0.5
	NDWC		0.7	0.7	0.8
	DMH		0.7	0.6	0.6
	NWHH		0.6	0.6	0.5
	WNAS		0.9	0.7	0.9
	NRCB		0.9	0.9	0.9
	NIS		0.9	0.8	0.9
	NAWS		0.3	0.6	0.8
	NSM		1.0	0.9	1.0
	NDWA		1.0	0.3	0.7
	NWMO		1.0	1.0	1.0

3.2. Standardised values of the indices

Figure 4 presents the standardised values of the different indices analysed by catchment on a scale of 0 to 1, where 0 represents the optimal situation and 1 the critical situation. Most of the indices are not far from critical point.



VULNERABILITY FACTORS	VULNERABILITY INDICES	STANDARDIZED VALUE OF INDEX (0 = very low to 1 = very high)		
		Uele	Aruwimi	Itimbiri
Exposure	SPEI	0.51	0.51	0.51
Sensitivity	NDVI	0.64	0.61	0.64
Adaptive capacity	FAI	0.90	0.90	0.80
	PFC	0.70	0.60	0.60
	PDQ	0.90	0.80	0.90
	NDP	0.80	0.60	0.50
	NSAP	0.90	0.90	0.70
	COP	0.70	0.60	0.50
	NDWC	0.70	0.70	0.80
	DMH	0.70	0.60	0.60
	NWHH	0.60	0.60	0.50
	WNAS	0.90	0.70	0.90
	NRCB	0.90	0.90	0.90
	NIS	0.90	0.80	0.90
	NAWS	0.30	0.60	0.80
	NSM	1.00	0.90	1.00
	NDWA	0.96	0.30	0.70
	NWMO	1.00	1.00	1.00

Figure 4. Standardised values of the indices related to the climate-water-migration-conflict nexus

The choice of weighting in aggregation significantly affects results. In this case study, the weighting was based on expert judgement, determined through a workshop involving various stakeholders focused on the climate water migration conflict nexus (CRREBaC, 2022) (Feindouno, Guillaumont, & Simonet, 2020). For the first aggregation, stakeholders agreed that adaptive capacity indices equally contribute to vulnerability and were assigned the same weight. In the second aggregation, exposure index (SPEI) were given a higher weight (3/4) than NDVI, sensitivity indices (1/4), as climate impacts were more evident in ecosystem changes. For the third aggregation, stakeholders agreed that in local conditions, potential impact (combining exposure and sensitivity) has a low weight (1/4) compared to adaptive capacity (3/4).

3.3.1. Composite index of potential impact

Table IV presents the composite index of potential impacts of the climate-water-migration-conflict nexus in the Uele, Aruwimi and Itimbiri catchments, obtained by aggregating the exposure and sensitivity factors. The results demonstrate that these three catchments exhibit a virtually identical composite index of potential impacts, evaluated at 0.54, which indicates a moderately critical vulnerability.

Table IV. Composite index of potential impact related to the climate water migration conflict nexus

Vulnerability factors	Weighting coefficient	Catchments		
		Uele	Aruwimi	Itimbiri
Exposure	3/4	0.51	0.51	0.51
Sensitivity	1/4	0.61	0.64	0.64
Potential impact	—	0.54	0.54	0.54

3.3.2. Aggregate index of vulnerability due to the climate water migration conflict nexus

Figure 5 illustrates the AVICC for the Uele, Aruwimi, and Itimbiri catchments. The results indicate that all three catchments are vulnerable to more than 60% of the moderate differences. The Aruwimi catchment is the most vulnerable (AVICC= 0.67), followed closely by the Itimbiri (AVICC= 0.65) and Uele (AVICC= 0.63) catchments. The results demonstrate an upward trend in vulnerability across all regions, emphasising the need for targeted strategies to enhance adaptive capacity, particularly in the Uele catchment.

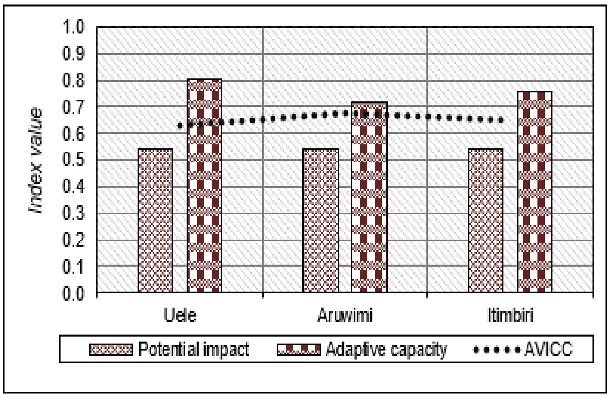


Figure 5. Aggregate vulnerability index due to the climate-water-migration-conflict nexus

4. Discussion

The vulnerability of a system to climate change is not a directly measurable attribute like temperature or precipitation. Rather, it results from a complex interaction between exposure to climate-related hazards, sensitivity of the system's ecological and socio-economic components, and its adaptive capacity (IPCC, 2007; Vincent, 2004). To capture this multidimensionality, we developed the AVICC, tailored to assess the vulnerability of catchments in the Congo Basin.

The AVICC framework provides a composite metric that enables the quantification of vulnerability levels by integrating environmental, hydrological, and socio-institutional dimensions. This approach aligns with widely recognized vulnerability assessment models such as the Climate Vulnerability Index (CVI) proposed by Sullivan & Meigh (2005), and Vincent's (2004) Social Vulnerability Index, both of which emphasize the pivotal role of adaptive capacity in shaping vulnerability outcomes, especially in tropical regions.

In the north-eastern Congo Basin, the application of AVICC reveals that the Aruwimi, Itimbiri, and Uele catchments are approaching critical vulnerability thresholds, with AVICC scores nearing 1. These values indicate significant exposure to the climate water migration conflict nexus, compounded by socio-economic fragilities. More than 60% of vulnerability levels across these catchments fall into the moderate to high category, with the Aruwimi catchment exhibiting the highest vulnerability, followed by Itimbiri and Uele. The primary driver of vulnerability in these catchments is low adaptive capacity, estimated at 80% for Uele, 75% for Itimbiri, and 72% for Aruwimi. These figures are alarmingly close to the AVICC critical threshold of 100%, highlighting deep-rooted institutional, technological, and economic constraints. This mirrors findings from other tropical basins, such as the Amazon, where socio-political marginalization and deforestation amplify climate risks (Saatchi et al., 2021; Zemp et al., 2017). Specifically, the comparative distribution of standardized vulnerability indices across the Uele, Aruwimi, and Itimbiri catchments (figure 4) shows that exposure and sensitivity indicators, particularly SPEI and NDVI, remain relatively consistent across the catchments, whereas adaptive capacity indicators display greater variability. Indices such as PDQ, NSM, NRCB, and NWMO maintain consistently high values, while NAWS and NDWA exhibit stronger spatial variation. Uele generally records higher adaptive-capacity scores, Aruwimi presents more moderate conditions, and Itimbiri shows a mixed vulnerability profile. The variability observed in adaptive capacity indicators suggests that the ability to respond and adapt to climate change impacts differs among the catchments, emphasizing that vulnerability is strongly influenced by local adaptive conditions and therefore requires locally tailored adaptation strategies (Parry et al., 2007; Pavageau et al., 2013).

Importantly, these findings underscore the urgency of investing in adaptive capacity-building measures in these catchments, including improved access to climate information, inclusive governance, water and food security systems, and gender-responsive adaptation strategies (IPCC, 2014; Karam et al., 2022). By applying the AVICC framework, policymakers and researchers gain a powerful tool for prioritizing interventions, monitoring systemic fragility, and designing context-sensitive adaptation pathways in complex tropical socio-ecological systems.

5. Conclusion

Understanding vulnerability to climate change remains a central challenge in both science and policy, particularly in regions like the Congo Basin, where social and ecological systems are highly interdependent and exposed to multiple stressors. Traditional approaches to quantifying vulnerability often fall short in capturing the complex, multi-scalar interactions between environmental drivers and socio-institutional dynamics. This study set out to address this gap by developing the Aggregate Vulnerability Index for addressing Climate Change (AVICC), a tool designed to assess and quantify the multidimensional nature of climate vulnerability in the Congo Basin.

Combining both quantitative and qualitative methodologies, the AVICC integrates data on climatic exposure, ecological sensitivity, particularly related to land cover change, and adaptive capacity based on socio-economic and institutional indicators. Through the aggregation and standardisation of selected indices, the AVICC supports more targeted vulnerability assessment and prioritisation of adaptation strategies.

The case study focused on the northeastern Congo Basin, where the Aruwimi, Itimbiri, and Uele river catchments were analysed under the lens of the climate water migration conflict nexus. Results indicate that all three catchments exhibit moderate to high vulnerability, with AVICC values nearing the critical threshold of 1, particularly in areas where adaptive capacity is severely constrained. The Uele catchment, for example, shows 80% low adaptive capacity, while Itimbiri and Aruwimi follow with 75% and 72%, respectively. These high levels of vulnerability are primarily driven by food insecurity, gender inequality, migration-related tensions, and weak governance systems.

Despite the current resilience conferred by the region's dense forest ecosystems, ongoing deforestation and socio-political instability threaten to erode this buffer. The findings confirm that environmental exposure alone does not determine vulnerability, institutional capacity, economic conditions, and social equity play critical roles. These insights align with global frameworks and underscore the necessity for integrated adaptation planning that transcends sectoral and disciplinary silos. Overall, this research demonstrates the relevance of the AVICC in informing climate resilience strategies for the Congo Basin. By offering a replicable framework, the study contributes to broader efforts aimed at operationalising climate vulnerability assessments and aligning them with the needs of at risk communities and ecosystems.

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Conflict of Interest

The authors declare no conflict of interest.

Ethics Considerations

This study did not involve human or animal participants. However, all field research adhered to institutional and national guidelines for environmental research ethics. Necessary authorizations were obtained from relevant local and provincial environmental authorities. In all cases where local community knowledge or land use was involved, the principles of free, prior, and informed consent were followed, respecting the rights and dignity of local populations.

Author Contributions

G.-S.K.L. and R.M.T. contributed to the conceptualization, methodology, software, and data collection.

G.-S.K.L., R.M.T., A.-R.M.N., and J.N.B.L. contributed to the formal analysis.

G.-S.K.L., A.-R.M.N., M.F., and O.N. contributed to writing, review, and editing.

R.M.T. and A.-R.M.N. supervised the study.

All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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