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RESEARCH ARTICLE
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Understanding Links Between Water Scarcity and Violent Conflicts in the Sahel and Lake Chad Basin Using the Water Footprint Concept

Elias Nkiaka[1], Robert G. Bryant[1], and Zongho Kom[2]

[1]Department of Geography, University of Sheffield, Sheffield, UK, [2]Department of Geography, College of Agriculture & Environmental Sciences, University of South Africa, Johannesburg, South Africa

Key Points:

- Water scarcity metrics are used to identify water scarcity hotspots and to understand the links between water scarcity and violent conflicts
- Water scarcity metrics show varying levels of water scarcity across the study area with capital cities being the most affected areas
- High green water scarcity (soil moisture deficit) and low Falkenmark index scores (water stress) are closely linked to water conflicts

Correspondence to:

E. Nkiaka,
e.nkiaka@sheffield.ac.uk

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Author Contributions:

Conceptualization: Elias Nkiaka
Formal analysis: Elias Nkiaka
Funding acquisition: Elias Nkiaka
Investigation: Elias Nkiaka, Robert G. Bryant
Methodology: Elias Nkiaka, Robert G. Bryant
Resources: Elias Nkiaka
Writing – original draft: Elias Nkiaka
Writing – review & editing: Elias Nkiaka, Robert G. Bryant, Zongho Kom

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Abstract

Whilst there are several empirical studies linking water scarcity and violent conflicts, existing quantitative studies use mostly climate and environmental variables even though such variables have been shown to not be strong predictors of water conflicts by some studies. The aim of this study was to use the water footprint concept and the Falkenmark index to identify water scarcity hotspots at the sub-national scale and to understand the links between water scarcity and violent conflicts in the Sahel and Lake Chad Basin over a period of two decades (2000–2021). We achieve this by developing five water scarcity metrics at a monthly timescale using runoff, soil moisture, potential evapotranspiration, water consumption and demographic data. The developed metrics show high levels of water scarcity across the study area during the dry, pre-monsoon and post-monsoon seasons. Analyses further reveal high green water scarcity (GWS) (soil moisture deficit) and low Falkenmark index scores (water stress) during the dry, pre-monsoon and post-monsoon seasons, across all reported water conflict locations. This suggest that there is an indirect link between GWS, the Falkenmark index scores and water conflicts. Results from this study may be used to enhance water management, mitigate, and prevent water conflicts in the study area and likewise the methodology adopted may be used to address water scarcity and conflicts in other regions.

Plain Language Summary

According to the IPCC Sixth Assessment Report, climate change is expected to increase the prevalence of conflicts across the world due to resources scarcity. The situation is expected to be exacerbated in regions with high population density, low socio-economic development, and high dependence on agriculture. Even though resources scarcity and conflict remain a topical issue within research and development arenas, establishing the direct link between the two has remained problematic. This may probably be due to a lack of an integrated approach to address this issue in a transparent way. Using an integrated approach involving several water scarcity metrics, this study shows that water conflicts in the Sahel and Lake Chad Basin are closely related to soil moisture deficit and population-driven water scarcity during different seasons of a calendar year. By developing different water scarcity metrics at the sub-national and seasonal scales, we have a clearer understanding of which water scarcity metrics are closely linked to conflicts and when water conflicts are prevalent. This implies that approaches to mitigate and prevent water conflicts may target specific water scarcity metrics and seasons within a calendar year.

1. Introduction

Several studies have warned that, water scarcity, one of the main causes of water insecurity will worsen in the coming decades due to different factors such as climate change, increasing population and economic growth (Distefano & Kelly, 2017; Schewe et al., 2014). This may in turn exacerbate food and energy insecurity (D'Odorico et al., 2018; Greve et al., 2018), ecosystem deterioration (Baggio et al., 2021) and context-centric violent conflicts related to resource scarcity (Almer et al., 2017; Regan & Kim, 2020). Anticipating an imminent global water crisis, the United Nations General Assembly adopted water security as one of the sustainable development goals (SDGs) with water scarcity included as one of SDG 6 targets. Water scarcity is defined in this study as a shortage in the amount of available physical water resources required to meet human and ecosystem needs. Water conflict is when there is a dispute over the control of water or physical access to water is restricted, or when water scarcity triggers violence; or when water resources/water systems are used as a weapon in conflict; or when water resources/water systems are targets during conflict (Gleick & Shimabuku, 2023; Gleick et al., 2023).

Globally, substantial progress has been made to provide evidence on the impact of water scarcity on different sectors of the economy (D'Odorico et al., 2018; Greve et al., 2018), and ecosystems (Baggio et al., 2021). Even though considerable research efforts have been deployed to show how resource scarcity especially water can trigger conflicts in different parts of the world (Almer et al., 2017; Bernauer & Böhmelt, 2020; Regan & Kim, 2020; Unfried et al., 2022; van Weezel, 2019), the number of intra-state water conflicts keep increasing globally especially in developing regions mostly attributed to physical resources scarcity (Almer et al., 2017; Galli et al., 2022; Regan & Kim, 2020; Unfried et al., 2022). The numerous case studies suggest that there exists a causal link between water scarcity and violent conflict. However, establishing a direct causal link using quantitative methods has been problematic probably because conflict occurrence is unpredictable both in space and time and therefore cannot be measured at intervals like timeseries data. As such, there is still a lack of an integrated quantitative approach that can be used to address this issue in a transparent manner. Several previous studies that investigated the link between water scarcity and conflicts adopted a qualitative approach underpinned by political ecology theories (Okpara et al., 2017; Selby & Hoffmann, 2014; Seter et al., 2018). Existing quantitative studies on this issue have often adopted climate variables (e.g., precipitation decline, increasing temperature and evapotranspiration index) and environmental stressors (e.g., vegetation failure) as predictors of water conflicts (Almer et al., 2017; Anderson et al., 2021; Regan & Kim, 2020; van Weezel, 2019). However, most of the quantitative studies that used climate variables and environmental stressors as predictors of water conflicts concluded that they are not strong predictors of water conflicts (Ayana et al., 2016; O'Loughlin et al., 2014; van Weezel, 2019). Whilst the use of water scarcity metrics as predictors of water conflicts is scarce, this approach is gaining traction within the academic literature. For example, Unfried et al. (2022) used mass water anomalies from GRACE satellite to establish the link between water scarcity and conflict. Galli et al. (2022) used water-availability data from an agro-hydrological model to analyze how hydrological factors influence conflict dynamics in the Lake Chad Basin (LCB). We observe that most of the quantitative studies focus on regional and national scales (e.g., Ayana et al., 2016; Regan & Kim, 2020; Unfried et al., 2022). Due to the coarse spatial resolution of data grid cells, such studies may fail to provide adequate information on the exact conflict location, even though such information may be critical for mitigating and preventing water conflicts at the sub-national scale. In addition, existing quantitative studies commonly incorporate conflicts induced by other socio-economic factors and only a few studies (e.g., Böhmelt et al., 2014; Döring, 2020; Kåresdotter et al., 2023) have addressed exclusively water conflicts. Whilst the inclusion of conflicts caused by other factors is of merit, their nature and scope of impact may be significantly different from those induced and/or exacerbated by water scarcity and a profound understanding of this complexity is needed for effective policy design (Funder et al., 2010).

The present study adopted two widely used water scarcity metrics including the Falkenmark index and the water footprint concept to understand the links between water scarcity and violent conflicts in the Sahel and LCB. The Falkenmark index is defined as the total renewable water resources that are available to the population of a given area per person per year/season. Water footprint is the total volume of freshwater that is used to produce the goods and services consumed by an individual or a community (Hoekstra et al., 2012). The water footprint concept comprises of blue and green water scarcity (GWS) indexes. We also developed the agricultural water scarcity (AWS) index defined as the ability of both blue and green water availabilities (GWAs) to satisfy the total agricultural water requirements (Liu et al., 2022). The water footprint concept has been used in several studies (e.g., Lathuillière et al., 2018). The Falkenmark index has also been used to identify population-driven water scarcity hotpots (Modi et al., 2022; Nkiaka, 2022d; Veettil & Mishra, 2020). Adopting an integrated approach with several water scarcity metrics ensures that results from this study can meet the needs of different stakeholders involve in water resources management. Moreover, we believe that formulating effective response strategies to address water scarcity challenges require a holistic understanding of the relative importance of each water scarcity metric at the sub-national scale.

This study seeks to fill three important research gaps in the water scarcity and conflict literature. First, we investigate whether water conflicts are driven by physical water scarcity by identifying water scarcity hotspots in the study area or whether water scarcity is driven by population pressure. Second, unlike previous studies that focused on regional and national scales or used coarse spatial grid cells and attributed all types of conflicts to water scarcity, the present study focuses exclusively on reported water conflicts using data at the sub-national scale. Lastly, the study adopts different water scarcity metrics to establish the indirect link between water scarcity and conflicts.

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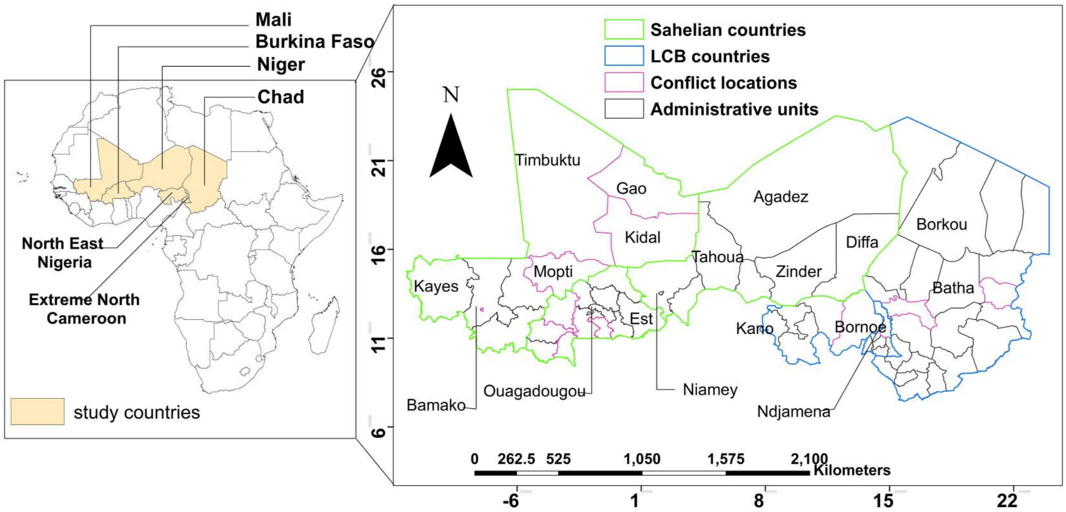

Figure 1. Map of countries encompassing countries in the central Sahel and LCB, different administrative units and conflict event location.

Therefore, the overarching goal of this study was to identify water scarcity hotspots and to establish the links between water scarcity and violent conflicts across the central Sahel and LCB at the sub-national scale using different water scarcity metrics. Specifically, we address (a) demand-driven water scarcity quantified in terms of green, agricultural, and blue water scarcities, (b) population-driven water scarcity quantified using the Falkenmark index, and (c) use the developed water scarcity metrics to establish the links between water scarcity and violent conflicts. Lastly, we discuss how socio-economic factors such as governance, human development index (HDI), fragile state index (FSI) and degree of implementation of integrated water resources management (IWRM) influence water conflicts in the study area. This is probably the first study to identify water scarcity hotspots in the target region using the water footprint concept. The study also contributes to the contemporary debate on water scarcity and conflicts by proposing an integrated method that uses multiple water scarcity metrics to establish the links between water scarcity and violent conflicts.

2. Material and Methods

2.1. Study Area

The central Sahel and LCB are found in central-west Africa (Figure 1). The climate is mostly semi-arid to arid with annual rainfall ranging from 200 to 1,200 mm/yr increasing from north to south while potential evapotranspiration (PET) ranges from 1,500 to 2,500 mm/yr increasing from south to north. The Sahel is remarkable due to a mega drought that hit the region from the 1970s to late the 1990s resulting to an international humanitarian emergency (Nicholson et al., 1998). The LCB is also famous due to the desiccation of Lake Chad from 25,000 to <4,000 km^2 as a result of climate change and unsustainable water management (Gao et al., 2011; Wine, 2022). Recent studies across the region have reported a gradual recovery in annual rainfall (Nkiaka et al., 2017). The Sahel and LCB have a unimodal rainy season lasting from June to September with mean annual temperature exceeding 18°C. The population is mostly agrarian and depend on rainfed agriculture and animal husbandry for livelihood.

The Sahel is one of the poorest and water-limited regions in the world, ranked amongst the most fragile ecosystems in the world and extremely vulnerable to the impacts of climate change (OECD, 2022). It is likely that Sahelian and LCB countries may not achieve SDG 6 by 2,030 due to a myriad of challenges including political instability, jihadist insurgency, poor governance, limited access to water and sanitation facilities and generalized insecurity (Nkiaka et al., 2021). Data analysis also shows increasing population across the region which [allied to likely water scarcity] may increase competition for water and the likelihood of conflicts among different water users' groups. Therefore, assessing water scarcity at sub-national scale across the Sahel and LCB and how this relates to the likelihood of water conflict is of paramount importance to underpin progress toward the achievement of water and food security, climate adaptation and to mitigate and prevent future water conflicts in the study area.

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Table 1
Administrative, Demographic, and Socio-Economic Characteristics of the Countries

Country	Number of administrative units	GDP per capita ($)	Country population (2020)	Governance index	HDI	FSI score	FSI rank	IWRM (%)
Burkina Faso	13	900	20,903,273	0.51	0.45	94	21/179	66
Cameroon	01	1,699	–	0.34	0.58	94	40/179	40
Chad	23	667	16,425,864	0.26	0.38	104.6	9/179	37
Mali	09	889	20,250,833	0.34	0.43	99.5	13/179	52
Niger	08	613	24,206,644	0.46	0.40	93.4	24/179	53
Nigeria	05	2,280	–	0.36	0.54	98	15/179	44

Note. N.B: We did not include the population of Cameroon and Nigeria because only part of the study area lies within the two countries. HDI, human development index; FSI, fragile state index; IWRM, integrated water resources management.

The study focuses on three countries in the central Sahel (Burkina Faso, Mali, and Niger) and three countries in the LCB (Chad, Cameroon, and Nigeria). The study area covers 59 administrative units with an estimated population of more than 110 million people. The geographic scope of this study transcends the traditional hydro-geographic domain commonly used in hydrology and adopts the administrative boundary extent which constitutes the limits of society water management assessment system (Lathuillière et al., 2018; Modi et al., 2022; Veettil & Mishra, 2020). Our analysis therefore focuses on first-tier administrative units called “regions” in Burkina Faso, Cameroon, Chad, Mali, and Niger and “states” in Nigeria. Shapefiles for the different administrative units were downloaded from GADM (www.gadm.org). GADM provides maps and spatial data for all countries at sub-national level. Table 1 provides information on key socio-economic and administrative characteristics of each country.

2.2. Datasets

2.2.1. Population Data

The study uses population data at the sub-national scale to estimate water scarcity in each administrative unit. Population data were obtained from the national statistical and census bureau of each country. Where the most recent sub-national population data was not available, we estimated the population using the discreet method (Haque et al., 2012) as follows:

$$X_t = X_0 * (1 + r)^t \quad (1)$$

where X_t is the population for the target year, X_0 is the population at time t_0, r is the population growth rate, and t is the number of years. The population growth rate for each country was obtained from the population division of the United Nations Department of Economic and Social Affairs (UNDESA, 2019). After estimating the sub-national population data for each administrative unit, the data was aggregated together to obtain the population of each country and compared with population data from UNDESA. Whilst the estimated population using the discreet method and that from UNDESA fall within the same range, there are slight discrepancies between the two datasets which may be attributed to the sources of data and the population growth rate used in the present study. Figure 2 shows the population density across the study area. The most densely population areas are the capital cities (Bamako, Ouagadougou, Niamey, and Ndjamena), followed by the five Nigerian states (Bauchi, Borno, Jigawa, Kano and Yobe), Extreme North region of Cameroon, and other areas in Niger, Burkina Faso, Mali, and Chad. Areas with high population density are located in the southern part of the study area while the north is generally less densely populated (Figure 3).

2.2.2. Socio-Economic Data

Governance data was obtained from world governance indicators (Kaufmann & Kraay, 2023). WGI provides information on six different dimensions of governance including voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of Law and control of corruption. Considering that the different indicators are provided in the range −2.5 to 2.5, we normalized the data into the range [0 1] using the following equation:

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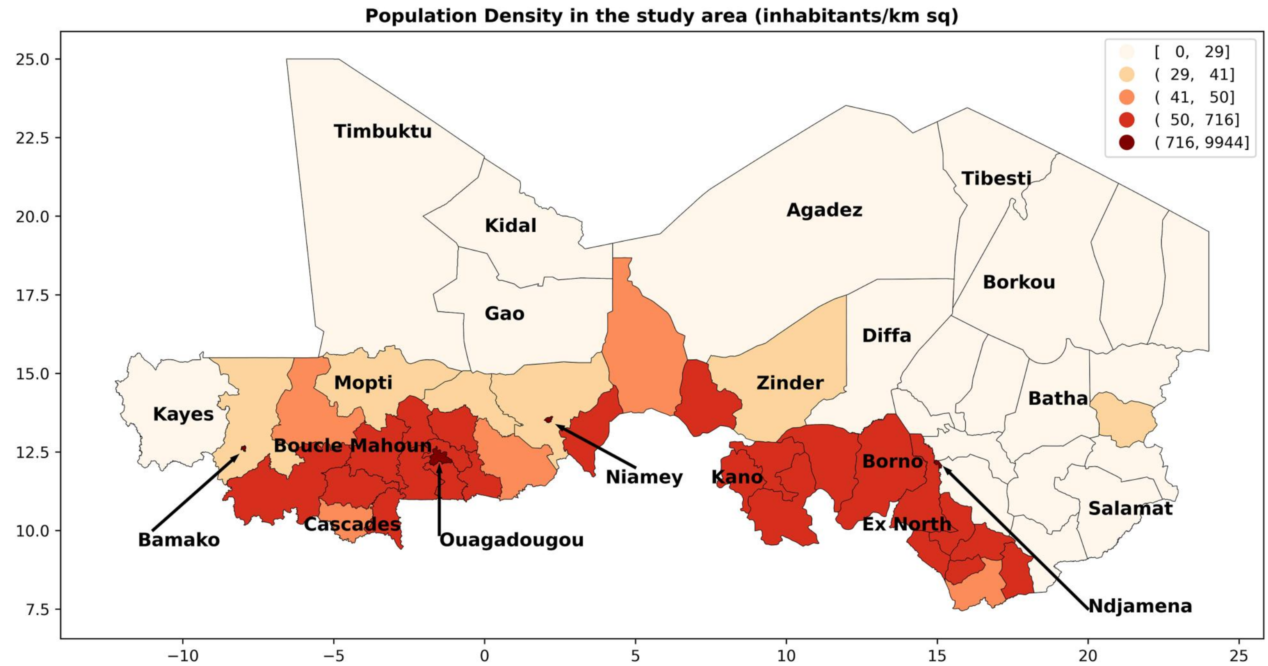

Figure 2. Population density across the different administrative units in the study area.

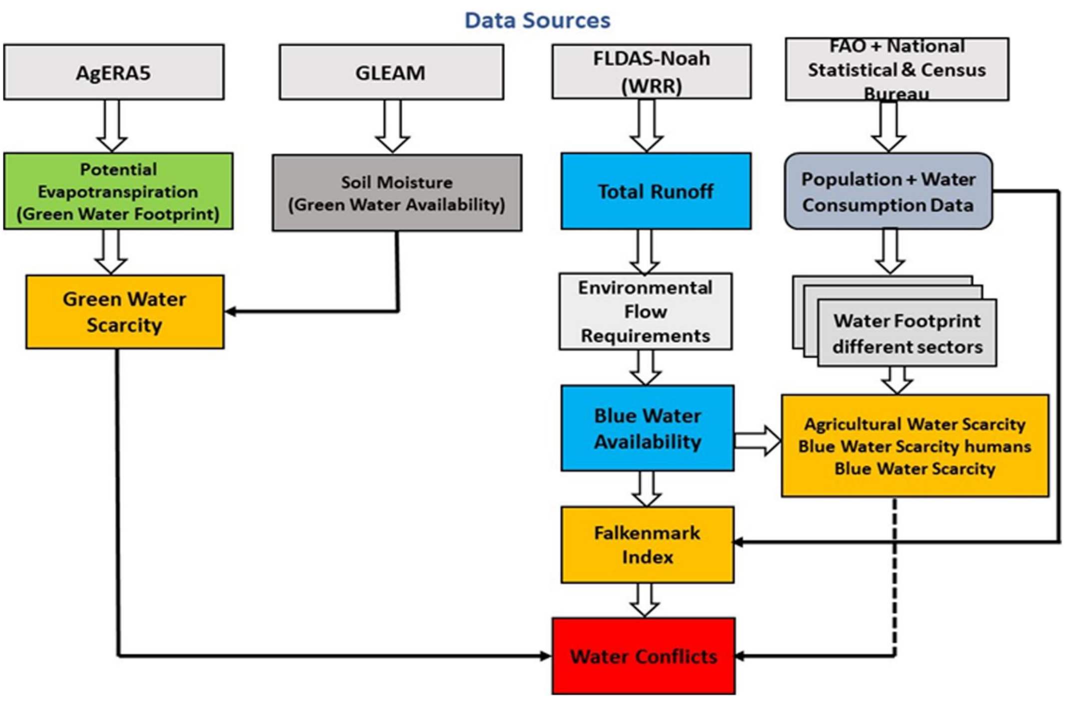

Figure 3. Flowchart outlining the data sources, steps used in developing the different water scarcity metrics and for establishing the link between the water scarcity metrics and violent conflicts. Details of each box in the figure are available in relevant sections of the paper. This Flowchart was created using Microsoft PowerPoint 365.

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$$N = \frac{X_{i-X_{min}}}{X_{max} - X_{min}} \tag{2}$$

where N is the normalized value, X_i is the observed variable, X_{min} is the minimum observed variable and X_{max} is the maximum observed variable. After normalizing the data, the arithmetic mean of the six dimensions was used as the governance index for each country. HDI provides information on the key dimensions of human development and data was obtained from the United Nations Development Program. The FSI is provided by the United States Fund for Peace. A fragile state is one where the state government is unable to or chooses not to provide the basic essentials to its people (Jiao, 2019). Data for IWRM and water stress was obtained from UN Water.

2.2.3. Runoff

To overcome the challenge of hydro-climatological data scarcity which is recurrent in the study area, we adopted runoff data from a global water resources reanalysis [WRR] (McNally et al., 2017). WRR are derived from global hydrological and land surface models that assimilate data from satellites to produce a range of water balance components including runoff. As such, WRR products can be used as reference to quantify blue water availability (BWA) at the local scale (Veettil & Mishra, 2020). WRR product used in this study is the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) with a spatial resolution of 0.1° at monthly timescale (McNally et al., 2017). Despite their numerous advantages, WRR products have generic limitations such as inherent biases and uncertainties and therefore need to be evaluated before use (Nkiaka et al., 2022). Regardless of known limitations, the use of WRR products in water scarcity assessments is growing because they can provide long-term homogeneous water availability data for previously unmonitored areas (McNally et al., 2019; Modi et al., 2022; Veettil & Mishra, 2020). FLDAS-Noah used in this study has been validated extensively across West Africa (McNally et al., 2017; Nkiaka et al., 2022), and also used in a previous study to estimate annual per capita water availability in Africa (McNally et al., 2019).

2.2.4. Soil Moisture

GWA is defined in this study as the water supply derived from soil moisture. The soil moisture was obtained from Global Land Evaporation Amsterdam Model (GLEAM). GLEAM is a process-based semi-empirical model used for estimating surface soil moisture, root-zone soil moisture, and terrestrial evaporation using satellite forcing data (Martens et al., 2017). GLEAM v3.7a was used in this study because it covers the longest available time period (1980–2021) at a monthly timescale with a spatial resolution of 0.25°. GLEAM soil moisture data was adopted because it has been validated in parts of Africa (e.g., Khosa et al., 2020), and recently used in a separate study in the Sahel (Wang et al., 2023). GLEAM soil moisture data used in this study comprise of surface soil moisture (0–10 cm) and root-zone soil moisture (10–100 cm) which is available for uptake by crops and other green vegetation to sustain evapotranspiration.

2.2.5. Potential Evapotranspiration (PET)

PET represents the total water requirement for crops and other green vegetation without water limitation. Although actual evapotranspiration (AET) is commonly used to represent green water flow (e.g., Nkiaka, 2022d; Veettil & Mishra, 2020), according to Liu et al. (2022), AET represents the actual water availability conditions which could be lower than the potential water requirements for crops and other vegetation due to water limitation. The authors argue that, using AET could underestimate green water flow because of limited water supply. In-line with this argument, the present study adopted PET to represent green water flow. PET data was obtained from AgERA5 with a spatial resolution of 0.1°. AgERA5 is different from ERA5 because it is tuned to finer topography, land use pattern and land-sea delineation of the ECMWF HRES model and is recommended for agriculture and agro-ecological studies (Boogaard et al., 2020). AgERA5 data have been used in west Africa to evaluate cocoa yield in Ghana (Asante et al., 2022). Green water flow or green water footprint in this study represents the amount of water that is expected to be lost through evapotranspiration from cultivated crops and other natural vegetation under unlimited water conditions.

Annual runoff, PET, and soil moisture data covering the period 2000–2021 were used to represent BWA, green water flow and GWA respectively. The water balance components represent the annual renewable water resources that can be exploited and are used in this study to estimate different water scarcity metrics at the sub-

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Table 2
Environmental Flow Requirements Defined by the Variable Monthly Flow (VMF) Method

Season	Definition	Recommended minimum monthly flow requirements
Low flow	MMF ≤ 0.4MAF	0.6MMF
Intermediate flow	MMF > 0.4MAF & MMF < MAF	0.45MMF
High flow	MMF > MAF	0.30MMF

Note. MMF, mean monthly flows; MAF, mean annual flows.

national scale. Runoff and PET data were downloaded using Climate Engine (Huntington et al., 2017). GLEAM v3.7a data were downloaded from the link provided at the end of this article.

2.2.6. Water Footprint Estimates

Water consumption data for each country was obtained from FAO AQUASTAT database averaged over the period 2018–2022. The data include total water withdrawal in agriculture, industry, municipal uses, and irrigation. Figure 2 shows the flow chart outlining the different steps used in developing the five water scarcity metrics and for establishing the links between water scarcity and violent conflict.

2.3. Water Scarcity Assessment

Water scarcity assessment was conducted at a monthly timescale and as such, all water scarcity metrics were developed at a monthly timescale. To facilitate the interpretation of results, water scarcity data for the different months in a calendar year were aggregated to seasonal timescale as follows: dry season: January, February, and March (JFM); pre-monsoon season: April and May, (AM); monsoon season: June, July, August, and September (JJAS) and post-monsoon season: October, November, and December (Dolan et al., 2021). Trend analysis for seasonal BWA and GWA was conducted using the non-parametric Mann-Kendal test while Sen's slope estimator was used to quantify trend magnitude and significance.

2.3.1. Green Water Scarcity

As stated earlier GWA refers to the root zone soil moisture (0–100 cm) representing the amount of soil moisture available for sustaining the growth of crops and other vegetation. The green water footprint or green water flow refers to the total water requirement for agriculture and other green vegetation without water limitation. GWS for administrative unit "x" and period "t" was calculated as the ratio between green water footprint and GWA as follows:

$$\mathrm{GWS} = \frac{\text{Green water footprint}}{\text{Green water availability}} \times 100\% \tag{3}$$

2.3.2. Blue Water Availability

Blue water is the amount of water that can be abstracted from surface and groundwater without affecting freshwater ecosystems, regardless of their accessibility (Liu et al., 2017). Runoff from FLDAS-Noah represent the sum of surface runoff and baseflow. The variable monthly flow (VMF) method (Pastor et al., 2014) was used to estimate environmental flow requirements (EFRs) for each month. The VMF method accounts for seasonality of runoff and flow regimes and follows the natural variability of the river by defining EFRs on a monthly basis. The method allocates 60% of mean monthly flow (MMF) to EFRs during the low-flow season while 40% of MMF can be withdrawn and allocates 30% of MMF to EFRs during the high-flow season. EFRs were estimated using the VMF method shown in Table 2.

After estimating EFRs, BWA for each administrative unit was estimated as the difference between total runoff and EFRs as follows.

$$\mathrm{BWA}_{(x,t)} = \mathrm{TR}_{(x,t)} - \mathrm{EFR}_{(x,t)} \tag{4}$$

where $BWA_{(x,t)}$ is the blue water availability, $TR_{(x,t)}$ is the total runoff, and $EFR_{(x,t)}$ is the environmental flow requirements.

Next, we estimated the agricultural water scarcity, which is described as the ability of both blue and GWAs to satisfy the total agricultural water requirements (irrigation, livestock, and aquaculture needs) of a given area (Liu et al., 2022). AWS was calculated as the ratio of agricultural water footprint to the sum of GWA plus BWA after EFRs and water withdrawal for other human uses have been satisfied:

$$AWS = \frac{\text{Agriculture water footprint}_{(x,t)}}{\text{Green Water Availability}_{(x,t)} + \left(TR_{(x,t)} - EFR_{(x,t)} - BWW_{os(x,t)}\right) * IE} \times 100\% \quad (5)$$

where $TR_{(x,t)}$ is the total runoff, and $EFR_{(x,t)}$ is the environmental flow requirements, $BWW_{os(x,t)}$ is the blue water withdrawal for other sectors and IE is the irrigation efficiency (IE). IE was obtained from Rohwer et al. (2007). National IE values were adopted at the sub-national scale.

In the next step, blue water scarcity (BWS_{humans}) for other human uses was estimated as the ratio between blue water footprint or water withdrawal for other human uses and BWA using the following equation:

$$BWS_{human(x,t)} = \frac{BWW_{os(x,t)}}{\left(TR_{(x,t)} - EFR_{(x,t)} - \text{Agriculture water footprint}_{(x,t)}\right)} \times 100\% \quad (6)$$

where BWS_{human} is the blue water scarcity for other human uses, $BWW_{os(x,t)}$ is the blue water withdrawal for other sectors, $TR_{(x,t)}$ is the total runoff, and $EFR_{(x,t)}$ is the environmental flow requirements. Other human water uses considered in this study include water withdrawal for municipal, industry, livestock, and aquaculture.

Blue water scarcity was estimated as the ratio between the total blue water footprint (withdrawal for agriculture and other human uses) and BWA after subtracting environmental flows.

$$BWS_{(x,t)} = \frac{\text{Total blue water footprint}_{(x,t)}}{TR_{(x,t)} - EFR_{(x,t)}} \times 100\% \quad (7)$$

Total blue water $\text{footprint}_{(x,t)}$ is the blue water footprint, $TR_{(x,t)}$ is the total runoff, $EFR_{(x,t)}$ is the environmental flow requirements and $BWS_{(x,t)}$ is the blue water availability. Water scarcity occurs when green, agricultural, and blue water scarcity exceeds 100%.

2.3.3. The Falkenmark Index

The Falkenmark index was used to estimate monthly per capita water availability or population-driven water scarcity estimated as the ratio between BWA and the population. The FLK Index [FLK(x)] was estimated as:

$$FLK_{(x)} = \frac{\text{Blue water availability}_{(x)}}{\text{Population}_{(x)}} \quad (8)$$

In total, five water scarcity metrics including GWS, AWS, BWS_{humans}, BWS, and the Falkenmark index were developed and used to quantify water scarcity at sub-national scale in countries located in the central Sahel and LCB.

2.3.4. Water Scarcity and Conflicts

To understand the relationship between water scarcity and violent conflicts, we used water conflict data covering the period 2000–2021 derived from (Gleick & Shimabuku, 2023). The data provides information on the conflict type (trigger, weapon, or casualty), year, country, and location. We summed up all the conflicts and number of fatalities recorded at each location over this period. Next, we analyze trends in seasonal BWA and GWA at each conflict location over the study period. The question we seek to answer using results of trend analysis is whether water conflicts are triggered by physical water scarcity which could be manifested by declining trends in seasonal

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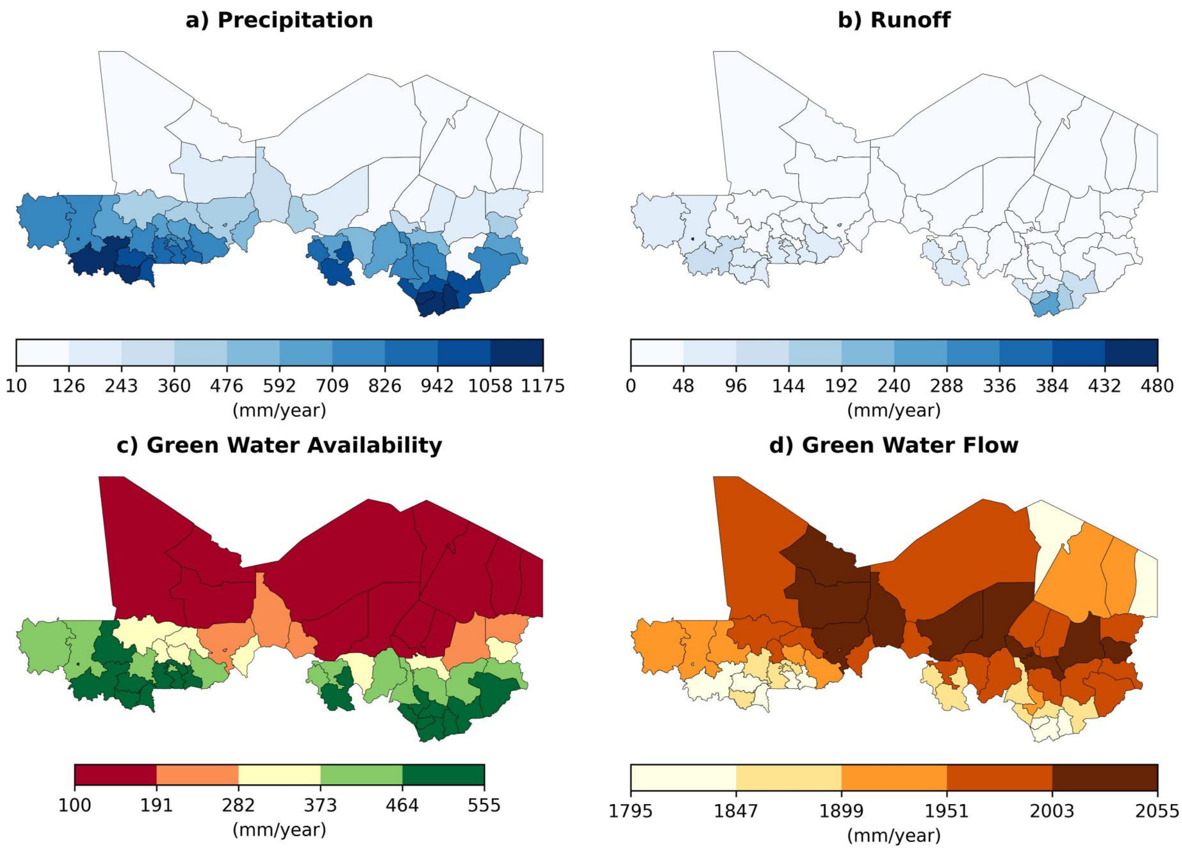

Figure 4. Spatial distribution of annual water balance components (a) precipitation, (b) runoff (blue water availability (BWA)), (c) green water availability (GWA) (soil moisture) and (d) green water flow (PET).

BWA and GWA or there are other factors such as competition from different users underpinning water conflicts. For example, a previous study in the Sahel has shown that farmer-pastoralist conflicts may be triggered by competition for declining water resources (Mertz et al., 2016). Lastly, the different water scarcity metrics were used to establish the relationship between water scarcity and violent conflicts by exploring which metrics that are closely associated with water conflicts.

3. Results

3.1. Spatial Distribution of Blue and Green Water, Green Water Flow and Population Distribution

The spatial distribution of the different water balance components averaged over two decades (2000–2021) is shown in Figure 4. Analysis shows that the spatial distribution of annual BWA and GWA is strongly associated with annual precipitation. Maximum blue water is recorded in the southern part of the study area particularly around Burkina Faso, northeast Nigeria, and southern Chad where mean annual blue water ranges from 48 to 384 mm/yr (Figure 4b). Similarly, maximum GWA is also observed in the southern parts of Burkina Faso and Chad where annual rainfall is equally very high (Figure 4c). Mean annual GWF (total water requirement for crops and other green vegetation without water limitation) ranges from 1,795 to 2,055 mm/yr across the whole study area with maximum values observed mostly around the northern portions of the study area.

3.2. Water Scarcity Assessment

GWS and AWS metrics across the study area are shown in Figure 5. It can be observed that GWS is high in the northern part of the study area irrespective of the season (Figures 5a–5d). However, GWS is substantially higher in the pre-monsoon season with index scores reaching 450% in parts of study area during this season (Figure 5b). Despite the high rainfall during the monsoon season, GWS remains relatively high in the northern part of the study

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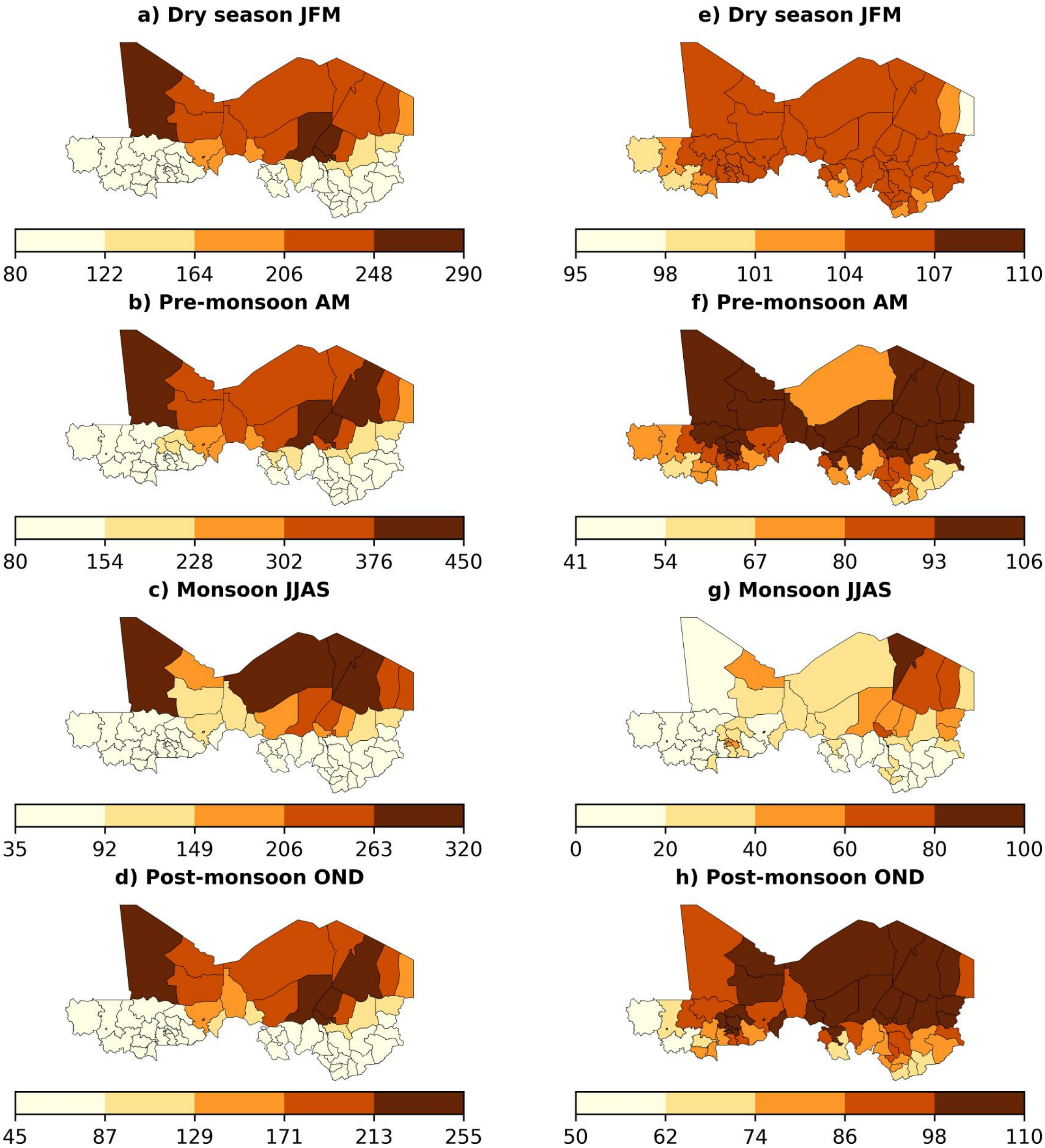

Figure 5. Spatial distribution of seasonal green water scarcity (GWS) (a)–(d) and (b) agricultural water scarcity (AWS) (e)–(f). The months are grouped into different seasons as follows: dry-January, February, March (JFM), pre-monsoon-April, May (AM), monsoon-June, July, August, September (JJAS), and post monsoon season-October, November, and December (Dolan et al., 2021).

area during this period even though the GWS index scores are substantially lower in the south (Figure 5c). AWS exceeds 100% in several locations across the study area during the dry and post monsoon seasons ranging from 101% to 110% (Figures 5e and 5h). However, AWS scores do not exceed 100% during the monsoon season when rainfall that contributes to soil moisture is at its peak (Figure 5g). Nevertheless, there is a strong spatial variability in AWS across the study area during the pre-monsoon season ranging from 41% to 106%. This implies that AWS may not be a significant challenge in the study area during this season (Figure 5f). Compared to GWS, we found that AWS is generally lower with a maximum score of 110% observed mostly during the dry and post monsoon seasons (Figures 5e and 5h) while GWS index scores reach 450% during the dry season (Figure 5b). Maximum AWS was observed mostly around the capital cities including Bamako-Mali, Ouagadougou-Burkina Faso, Niamey-Niger, Ndjamena-Chad (Figures 5e–5h). Considering individual countries, we found that GWS is particularly high in the northern regions of Mali, Niger, and Chad with AWS index scores displaying a similar pattern across these countries (Figures 5e–5h).

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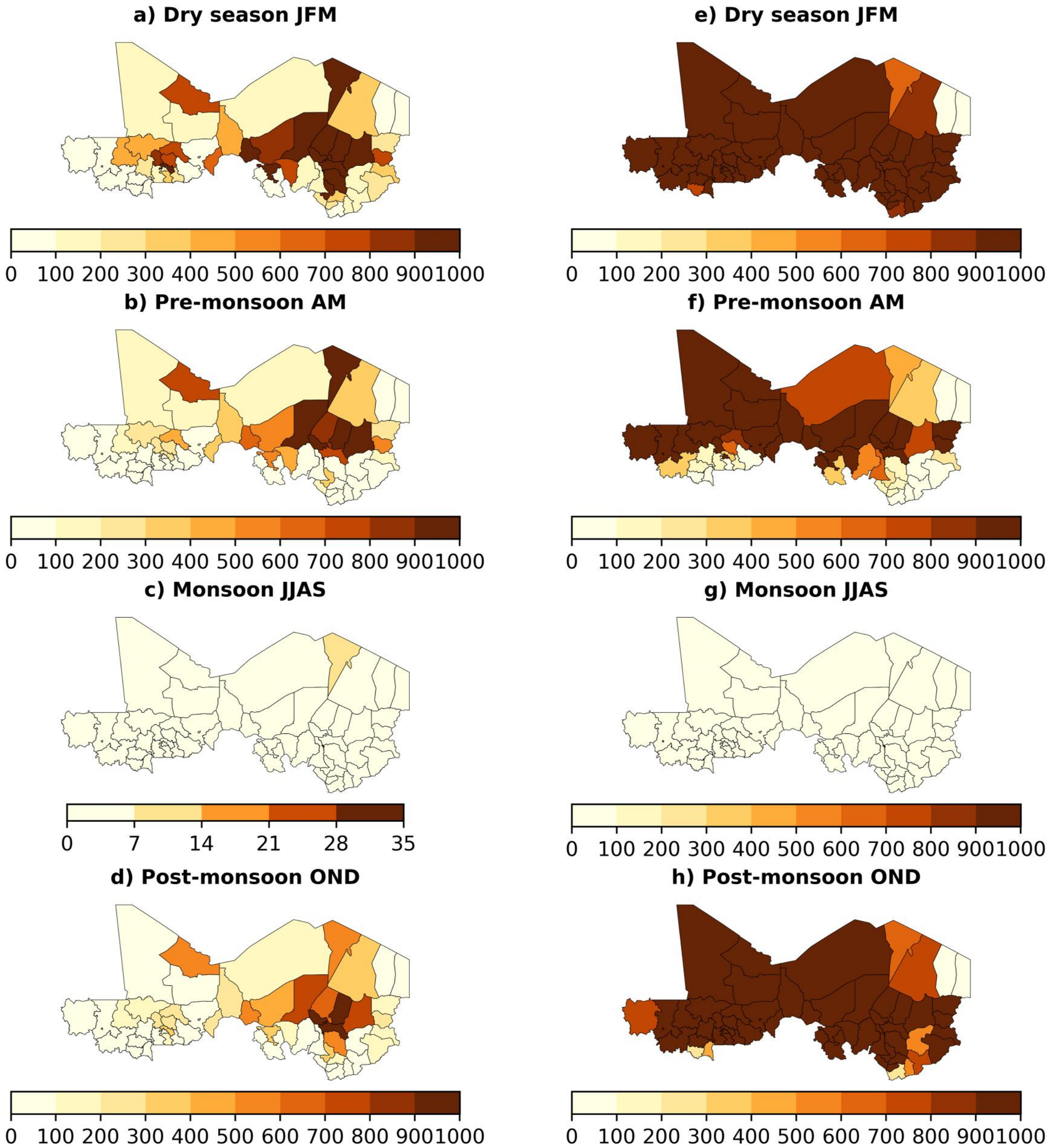

Figure 6. Spatial distribution of seasonal BWS_{humans} (a)–(d) and (b) BWS (e)–(f). The months are grouped into different seasons following the approach in Figure 5. BWS_{humans} include water used for municipal, industrial, livestock and aquaculture.

Figure 6 shows the spatial distribution of BWS_{humans} and total BWS across the study area. It can be observed that there is a strong spatial variability in BWS_{humans} during the dry, pre-monsoon and post-monsoon seasons with BWS_{humans} index scores exceeding 1,000% in several locations during these seasons (Figures 6a, 6b and 6d). However, BWS_{humans} is substantially low in some locations during the pre-monsoon season and only a few locations such as Kanem, Tibesti, and Ndjamena (Chad), Kidal and Diffa (Niger) display substantially high BWS_{humans} index scores (Figure 6b). On the other hand, BWS_{humans} ranges from 0% to 35% across the study area in the monsoon season (Figure 6c) suggesting that no scarcity is reported for this specific water scarcity metric during this period of the year. Similarly, total BWS is substantially high across most of the study area during the dry, pre-monsoon and post-monsoon seasons (Figures 6e, 6f and 6h). Despite the substantially low BWS index scores during the monsoon season, Ndjamena (Chad) has significantly high BWS index score exceeding 1,000% which suggest that BWS is a major challenge in this city throughout the calendar year.

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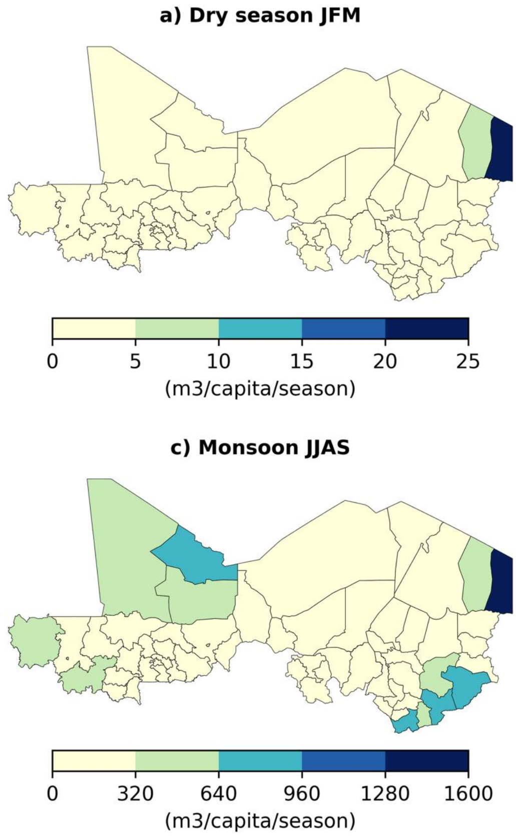

Figure 7. Spatial distribution the Falkenmark Index across the study area. The months are grouped into different seasons following the approach in Figure 5. The Falkenmark index scores were obtained by estimating the mean of the different months in each season.

Figure 7 show the Falkenmark index scores across the study area. According to Falkenmark et al. (1989), when the Falkenmark index score is above 1,700 m^3/capita/yr this implies that there is no water stress in a region/country. After considering EFRs, the monthly Falkenmark index was obtained by dividing 1,700 m^3/capita/yr by 12. Therefore, the average monthly Falkenmark index score is considered as 142 m^3/capita/month for a region that is free from water stress. Taking this as a reference, it can be observed that population-driven water scarcity is widespread in the study area during the dry, pre-monsoon and post-monsoon seasons when the Falkenmark index score is generally below the mean monthly index score of 142 m^3/capita/season across most areas. However, there is slight improvement during the monsoon season when the minimum Falkenmark index score increases to 320 m^3/capita/season across several locations and even exceeds 1,200 m^3/capita/season in a few places (Figure 7c). However, it worth highlighting that the northern regions of Chad and Mali where the Falkenmark index scores are relatively high are also less densely populated.

3.3. Water Scarcity and Conflicts

Table 3 summarizes the conflict characteristics at each location and provides the slope magnitudes of seasonal trends in BWA and GWA at the different conflict locations. Data from water conflict database show that from January 2000 to December 2022, 21 water conflicts were registered across the Sahel and LCB resulting to 410 fatalities. Date future show that water was both a trigger and casualty in 16 and five conflicts respectively. Nine conflicts were reported in Mali that caused 299 fatalities, 6 were reported in Burkina Faso resulting to 47 fatalities, Chad registered three conflicts that led to 41 fatalities and two conflicts were reported in Cameroon resulting to 23 fatalities. One conflict was reported in Nigeria with no fatality while no single conflict was reported in Niger

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Table 3
Conflict Characteristics and Trends in Seasonal Blue and Green Water Availability

Country	Conflict location	Casualties	Population density (persons/km^2)	Blue water availability (mm/month)				Green water availability (mm/month)			
				Dry season	Pre-monsoon	Monsoon	Post-monsoon	Dry season	Pre-monsoon	Monsoon	Post-monsoon
Mali	Bamako (1)	None	9,945	−0.01	0.01	**1.32**	0.21	0.65	0.59	1.15	0.11
	Timbuktu (1)	5	2	**0.01**	0.001	**0.009**	−0.001	0.13	0.31	**1.58**	0.22
	Mopti (6)	290	36	**0.01**	0.002	**0.12**	0.005	**2.55**	**2.1**	**4.11**	3.19
	Gao (1)	4	5	0	**0.01**	0.01	0.001	0.15	0.05	**4.62**	−0.24
Burkina Faso	Center-Sud (1)	None	70	0.01	**0.07**	**0.44**	**0.12**	**0.77**	0.06	−0.41	0.11
	Southwest (4)	47	55	0.01	0.03	**0.54**	**0.16**	0.03	−0.21	−1.51	0.39
	Boucle du Mahoun (1)	None	56	**0.01**	0.02	**0.37**	**0.04**	**1.32**	0.15	1.35	1.87
Chad	Ouaddai (2)	35	35	0	−0.005	0.13	**0.004**	−0.14	−0.22	1.78	1.67
	Hadjer Lamis (1)	6	27	0	−0.002	**0.04**	0	**0.95**	0.26	**2.41**	**2.24**
Cameroon	Extreme North (2)	23	132	−0.01	0.01	0.31	0.02	**0.47**	0.54	1.18	0.71
Nigeria	Borno state (1)	None	41,743	0	0.002	0.25	0.01	**0.73**	**0.59**	0.86	0.19

Note. Figures in bracket in column 2 represent the number of conflicts events registered at each location while figures in bold indicate statistically significant trend at 5% significance level.

(Table 3). Trend analyses show consistent increase in BWA during the monsoon season while the results are mixed with both significant and non-significant increasing trends during the other seasons. Analyses also show non-significant declining trends in BWA in some conflict locations during the dry season (Table 3). For GWA, trend analyses show consistent increase across most locations irrespective of the season with significant trends recorded in six locations in the dry season. However, GWA also show declining trends in two locations in Burkina Faso during the monsoon season.

Figure 8 provides a summary of the different water scarcity metrics estimated for each conflict location for the different seasons. It can be observed that GWS exceeds 100% (indicating scarcity) at almost all locations during the dry and pre-monsoon seasons while falling below 100% (indicating no scarcity) in most locations during the monsoon season (Figure 8a). However, GWS exceeds 100% in Timbuktu and Gao during the monsoon season suggesting that the available soil moisture cannot meet atmospheric demand in these locations throughout the year. AWS slightly exceeds 100% mostly during the dry and pre-soon seasons while remaining generally below 100% for the rest of the seasons which suggests that AWS is not a major challenge in the reported water conflict locations (Figure 8b). $BWS_{–humans}$ exceed 100% at several locations during the dry and pre-monsoon seasons with Mopti, Center-Sud (Burkina Faso) and Ouaddai and Hadjer-Lamis (Chad) being the most affected locations (Figure 8c). Total BWS is a major challenge exceeding 1,000% across all conflict locations during the dry, pre-monsoon and post-monsoon seasons (Figure 8d). The monthly Falkenmark index also show substantially low scores across all conflict locations, exceeding the minimum threshold of 142 m^3/person/month only in three conflict locations during the monsoon season (Figure 8e). This suggest that the level of water stress in all the water conflict locations is substantially high throughout the year.

4. Discussion

The overarching goal of this study was to identify water scarcity hotspots using different water scarcity metrics and to use the metrics to establish the links between water scarcity and violent conflicts in the central Sahel and LCB. In this section, we discuss the key results of our analyses.

4.1. Spatial Distribution of Blue Water, Green Water Flow, and Green Water Storage

The distribution of BWA, GWA follows rainfall distribution across the study area while the spatial distribution of GWF follows the regional climatology. This is not unexpected considering that rainfall is the major factor that

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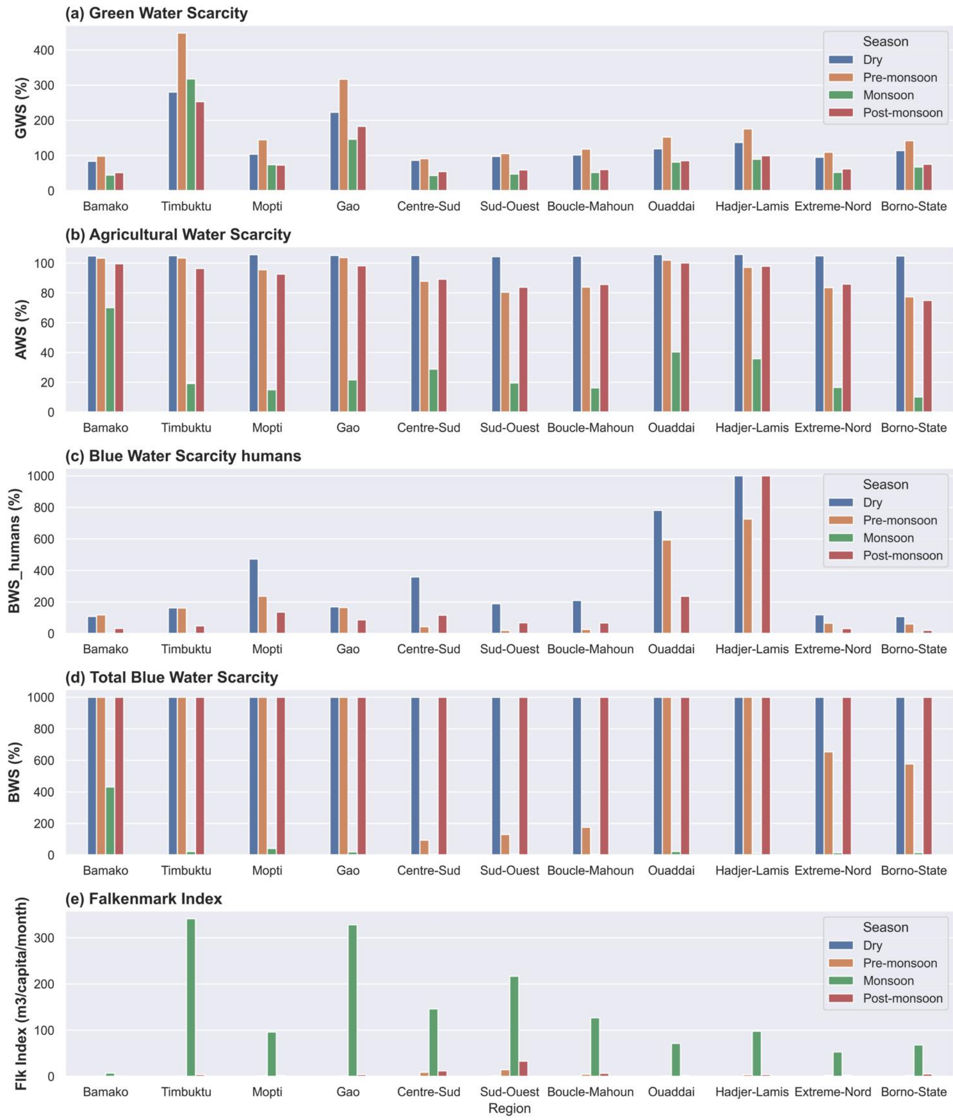

Figure 8. Water scarcity metrics for the different reported water conflict locations and seasons. The months are grouped into different seasons following the approach in Figure 5.

drives most processes in the hydrological cycle including runoff, baseflow, recharge, evapotranspiration and soil moisture storage which control water availability (Nasta et al., 2020). However, it is important to note that these components of the hydrological cycle are also strongly influenced by other physical characteristics of the landscape such as topography, land cover and soil characteristics (Awotwi et al., 2015). However, we did not consider the impact of these other factors in our water scarcity assessments. Analyses also show that some urban areas with relatively low annual rainfall such as Bamako-Mali, Ouagadougou-Burkina Faso, and Niamey-Niger produce high BWA.

Whilst high BWA is suggestive of abundant blue water, it may not necessarily be the case due to other factors such as accessibility and temporal distribution. Indeed, one of the limitations of BWA estimate is that, while it can show the amount of blue water, it fails to indicate whether the water is readily accessible. Therefore, high BWA does not suggest that the water is readily available for withdrawal; rather it could be an indication of floods as a result of urbanization which has the potential to increase surface runoff because of an increase in impervious areas (Anarfi et al., 2020; Tazen et al., 2019). Therefore, high BWA in urban areas in the study may not be considered as an asset for attenuating water scarcity thereby highlighting a need to develop appropriate infrastructure that may be used to capture and store this water during peak flow periods. Considering that we used PET to represent the

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total water requirement for crops and other green vegetation without water limitation, areas with relatively higher temperature equally exhibit higher PET values which reflects the extent of atmospheric water demand in those areas.

4.2. Water Scarcity Metrics

Analyses show that GWS is relatively high in the northern portion of the study area irrespective of the season which reflects the low rainfall in this area given that rainfall is the main source that replenishes soil moisture. Analyses also reveal relatively lower GWS in the southern parts of the study area during the monsoon and post-monsoon seasons which reflects the high amount of rainfall recorded during the monsoon season which is enough to replenish soil moisture to sustain GWF during the two seasons. This suggest that GWA can meet the water requirements of crops and other green vegetation without limitation during the two periods. Meanwhile, in the northern portion, GWA cannot satisfy the water requirements for crops and other green vegetation without limitation irrespective of the season. While GWS is a big challenge in the northern part of the study area irrespective of the season, the southern part is only affected during the dry and pre-monsoon seasons when soil moisture is completely depleted by high atmospheric water demand during this period. Analyses further reveal that AWS does not exceed 100% during the monsoon season while in the rest of the seasons, it reaches 110% in the dry and post monsoon seasons. This suggest that AWS does not appear to be a big challenge in the study area throughout the year because the GWA (soil moisture) plus BWA after satisfying EFRs and water withdrawal for other human uses can meet the water demand in agriculture (irrigation, livestock, and aquaculture) in most of the seasons.

BWS_{humans} after subtracting EFRs and meeting agricultural water demand cannot meet the human water needs for other sectors (industry, municipa supply, livestock, and aquaculture) in the other three seasons except the monsoon season. Apart from the monsoon season when BWS_{humans} is less than 100%; throughout the rest of the seasons, it exceeds 100% even reaching 1,000% in a few areas which indicates acute scarcity. This may be due to high population density in some areas which increases the total water demand. Specifically for capital-city regions, high BWS_{humans} may be attributed to the fact that most industries in the region are probably located in the capital cities which increases the demand for water. Analyses also reveal that the total BWS is exceptionally high across most areas throughout the year except during the monsoon season. Even during the monsoon season, BWS still exceeds 1,000% in Ndjamena. This suggest that Ndjamena (Chad) is affected by BWS throughout the year as the available blue water cannot meet the water demand of the city. Even though BWS is relatively low across most areas during the pre-monsoon and monsoon seasons, it does not necessary imply that the available blue water is readily accessible to the population. For example, a recent study assessing the state of SDG 6 in Africa found that access to water services and not water scarcity was the major factor impeding the attainment of SDG 6 in many countries (Nkiaka et al., 2021).

Assuming a mean monthly Falkenmark index score of 142 m^3/capita/month as a threshold for a region that is free from water stress, analyses show that this threshold is achievable in most locations only during the monsoon season when there is high rainfall in the study area. In contrast, no location achieved this threshold in the dry, pre-monsoon and post-monsoon seasons indicating absolute water stress. To reduce the water stress in during seasons, additional measures such as rainwater harvesting (capturing and storing excess blue water during floods), enhancing IE, and water use efficiency across all sectors may be implemented. Analyses also suggest that urban water scarcity is a major challenge which is consistent with results from another study in West Africa (Keough & Saidou, 2021). This suggest that urban water scarcity in the central Sahel and LCB must be tackled as a matter of urgency.

4.3. Water Scarcity and Conflicts

Analyses indicate increasing trends in seasonal BWA and GWA in most conflict locations even though there are a few locations where declining trends were observed which is generally consistent with increasing trends in seasonal and annual rainfall in the region (Nkiaka et al., 2017). Despite the increasing trends in seasonal GWA across most conflict locations, GWS remains substantially high (>100%) in most locations especially in the dry and pre-monsoon seasons. This suggest that the increasing trends in GWA during these seasons has not yet reached the level that can off-set soil moisture deficit in those locations. High GWS can lead to poor vegetation growth especially pasture which is a critical resource for animal husbandry in the region. Previous studies have

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identified the scarcity of pasture during the dry season as the source of most farmer-pastoralist conflicts in the region (Brottem, 2020; Mertz et al., 2016). This suggest that water related conflicts are more likely to occur during the dry and pre-monsoon seasons when GWS is particularly high in the study area (Anderson et al., 2021). Approaches to mitigate and prevent water conflicts in the region may therefore target these seasons.

The mean monthly Falkenmark index score across all conflict locations is below the 142 m^3/capita/month threshold in the dry, pre-monsoon and post-monsoon seasons and only exceeds this value at three locations during the monsoon season. This indicates the prevalence of absolute water stress throughout the year at most conflict locations. The implication of this finding is that population-driven water scarcity or water stress may be an important factor underpinning water conflicts in the study area because high population density can increase the pressure on water resources leading to competition among water users. This is in-line with findings from other studies reporting that in areas facing water scarcity, conflicts were more prevalent in areas with high population densities (Pearson et al., 2021; Østby et al., 2011). Among all the water scarcity metrics developed, we found that GWS and the Falkenmark index scores are more closely linked to water conflicts. This is because GWS index and the Falkenmark index scores were substantially high and low respectively in the dry, pre-monsoon and post-monsoon seasons across all reported water conflict locations. We therefore posit that there is an indirect link between the two metrics and water conflicts in the different seasons.

Analyses also reveal that 76% of conflicts are directly linked to water scarcity despite increasing trends in BWA and GWA. This may be attributed to other immediate or remote socio-political reasons such as disputes over the control of water resources or restricted access to water sources which is in-line with findings reported by Tir and Stinnett (2012). Their study found that though water scarcity could increase the likelihood of conflict occurrence, socio-economic and governance factors such as the lack of effective joint monitoring, and efficient treaty execution were the main explanatory factors where there were disputes over water resources management. In fact, we observe that all the countries in the study area rank low in governance, HDI and the degree of implementation of IWRM. For example, high degree of implementation of IWRM can reduce intra-state water conflict because it encourages coordination and build trust among the different stakeholders involve in water management. On the other hand, good governance and high HDI can ensure effective joint monitoring, efficient treaty execution and reduce social inequality which has been shown to exacerbate resources conflicts (Østby et al., 2011). The low ranking of countries in the above socio-economic index scores including GDP per capita may therefore limit the capacity of governments to design and implement policies aimed at mitigating and preventing water conflicts. Low GDP per capita may also limit the capacity of governments to build the required water infrastructure (Nkiaka, 2022b), which is essential to enhance access to water services (Unfried et al., 2022). Previous studies in the region have attributed resource conflicts to several factors including poor governance (Benjaminsen & Ba, 2019; Brottem, 2020; Seter et al., 2018). All the countries also show high FSI scores with most of them ranked among the top fragile states in the world which suggests that the countries are very vulnerable to conflicts occurrence and hence a simple dispute may easily degenerate to conflict.

It was also observed that although many areas in Niger have low Falkenmark index scores (high water stress), high GWS and the country also ranks low in all socio-economic dimensions, no water conflicts were reported in Niger. This suggest that there may be other local factors exacerbating or inhibiting water conflicts in countries in the study area. Additional research may therefore seek to investigate the role of local factors such as culture and religion given their potential to inhibit resources conflict because of their strong influence in fostering social cohesion (Abu-Nimer & Smith, 2016).

Our analyses show that by combining biophysical (runoff, soil moisture, and PET), water consumption and demographic data, it is possible to identify water scarcity hotpots at the sub-national scale. Results from such analyses may be crucial for putting in place measures to mitigate and prevent potential water scarcity conflicts in the wake of increasing global water crisis and intra-state water conflicts. For example, water conflicts in the region can be mitigated through the provision of customized seasonal and sub-seasonal forecast information related to soil moisture anomalies and runoff (water availability) to different stakeholders (Boult et al., 2020). Another key policy option may be the development of appropriate infrastructure for rainwater harvesting to alleviate blue water scarcity during the dry, pre-monsoon and post-monsoon seasons.

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5. Study Limitations

Due to data scarcity, the study adopted mostly secondary data. Although most of the datasets including FLDAS-Noah WRR, GLEAM soil moisture, PET from AgERA5 have either been validated or used in previous studies in the region, we wish to acknowledge that the datasets are not free from inherent uncertainties which may potentially influence the results of our analyses. Furthermore, we did not include groundwater availability in our blue water scarcity assessment due to a lack of data related to groundwater availability and use. We acknowledge that the inclusion of groundwater availability data may likely off-set the blue water scarcity metrics estimated in this study. Nevertheless, runoff remains the most readily available water source in the region as access to groundwater may be restricted by lack of infrastructure. Furthermore, the population data used in the study may also not reflect the actual population in the study area due to the constant movement of people in the Sahel and LCB as a result of recurrent armed conflicts, political instability, and jihadist insurgency. Such population movement may strongly influence the water scarcity metrics developed in this study. Another limitation of the study is that due to a lack of relevant data, gray water footprint which is one of the three categories of the water footprint concept was not considered in the different water scarcity metrics. Due to these limitations, we wish to remind out readers to regard the results from this study with some caution. Contingent on the data becoming available, future research may seek to incorporate groundwater availability and gray water footprint in water scarcity assessment in the study region.

6. Conclusions

The overarching goal of this study was to identify water scarcity hotspots and to understand the links between water scarcity and violent conflicts in the central Sahel and LCB using the water footprint concept and the Falkenmark index. To achieve this, five water scarcity metrics were developed including GWS, AWS, blue water scarcity for human use, total blue water scarcity and the Falkenmark index. Results reveal widespread GWS, BWS_{humans} and total BWS during the dry, pre-monsoon and post-monsoon seasons. Population-driven water scarcity (water stress) is also a major challenge especially during the dry, pre-monsoon and post-monsoon seasons as the Falkenmark index score is below 142 m^3/capita/month threshold across most areas.

Analyses also reveal that GWS index and the Falkenmark index scores are substantially high and low respectively in the dry, pre-monsoon and post-monsoon seasons in all reported water conflict locations. This suggest that there is an indirect link between the two water scarcity metrics and water conflicts. From the results obtained, we posit that, water conflicts in the central Sahel and LCB may be attributed to soil moisture deficit and population-driven water scarcity (water stress). There are also areas with high GWS and low Falkenmark index scores where no water conflicts were reported which suggest that there may be other factors other than physical water scarcity exacerbating or inhibiting water conflicts in the study area.

The method adopted in this study has allowed us to identify critical water scarcity hotspots in the study area. Our findings show that water conflicts cannot be explained by hydrological factors alone without incorporating other socioeconomic factors such as water consumption and demographic data. Results from this study may be used by stakeholders to enhance water management and mitigate water conflicts in the region. The same approach may also be used to enhance water management and mitigate water conflicts in other regions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Shapefiles for the different administrative units were downloaded from GADM available at www.gadm.org (last accessed: 22nd November 2022). World Governance Indicators were obtained from www.worldbank.org/governance/wgi/ (last accessed 13th June 2023). Human Development Index 2021 was obtained from www.hdr.undp.org/data-center/human-development-index#/indicies/HDI (last accessed: 6th June 2023). Fragile State Index 2021 was obtained from www.fragilestatesindex.org (last accessed: 6th June 2023). IWRM implementation and water stress data were obtained from www.sdg6data.org (last accessed: 6th June 2023). Outputs from FLDAS-Noah WRR are available from Climate Engine: https://app.climateengine.com/climateEngine (last accessed: 21st November 2022 using a customized users' account). Water consumption data was obtained from FAO AQUASTAT https://www.fao.org/aquastat/en/ (last accessed: 15th September 2022). Water conflict data were obtained from www.worldwater.org/conflict/list/ (last accessed: 15th November 2022). GLEAM data is available for download from www.gleam.eu (last accessed: 6th June 2023). Population data for each country were obtained from the following sources: Burkina Faso: https://www.servicepublic.gov.bf/ (last accessed: 22nd November 2022). Cameroon: http://www.bucrep.cm/ (last accessed: 22nd November 2022). Chad https://www.inseed.td/ (last accessed: 22nd November 2022). Mali: https://instat-mali.org/fr (last accessed: 22nd November 2022). Niger: https://www.stat-niger.org/ (last accessed: 22nd November 2022). Nigeria: https://www.nigerianstat.gov.ng/ (last accessed: 22nd November 2022). We have uploaded datasets containing shapefiles of all administrative units in our study area in an online repository (Nkiaka, 2022a). Data for all the variables used in producing Figures 4–7 have also been uploaded in an online repository (Nkiaka, 2022c).

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