Regional Environmental Change (2026) 26:183
https://doi.org/10.1007/s10113-026-02664-1

RESEARCH

Dynamics of human adaptation to flood risk in the Sudd wetlands, South Sudan

Deng Majok Chol[1] · Amelie Paszkowski[1] · Kevin G. Wheeler[1] · Steve Smith-Kroll[2] · Jim W. Hall[1]

Received: 15 October 2025 / Accepted: 7 August 2026 / Published online: 2 September 2026
© The Author(s) 2026

Abstract

The Sudd is the largest tropical wetland in the world, and its ecosystem services are fundamental to the livelihoods, well-being, and cultural systems of communities living within the region. Although human adaptation to seasonal flooding has long been a defining feature of socio-ecological interactions in the Sudd, changing flood dynamics increasingly challenge existing adaptation pathways. This study investigates the changing dynamics of human adaptation to flood risk among flood-affected populations through an empirical assessment of community experiences and responses. Using a mixed-method approach combining focus group discussions, semi-structured interviews, participatory mapping, and field observations, we conducted a thematic analysis of locally grounded evidence. The results reveal that unprecedented flooding between 2019 and 2022 produced severe disruptions to livelihoods, settlements, mobility patterns, and social systems across the Sudd. Communities reported strong perceptions of a shift in flood regimes, characterized by increased flood magnitude, expanded inundation extent, and prolonged periods of water persistence. These changes have altered established patterns of mobility, with temporary displacement increasingly evolving into longer-term migration and, in some cases, permanent relocation among pastoralist and sedentary populations. Migration occurs across multiple spatial scales, including within states, between states, and across national boundaries, resulting in the abandonment of some flood-prone settlements. The study also develops a spatio-temporal socio-hydrological framework that conceptualizes flood adaptation as a dynamic process operating across interconnected household, community, regional, and national scales over time. The framework advances understanding of how hydrological change, migration, governance, and social transformation shape adaptation pathways in the Sudd and other climate-sensitive wetland systems. These findings demonstrate that strengthening flood resilience requires adaptation strategies that integrate hydrological change with local knowledge, mobility, and social institutions. By providing rare empirical evidence from one of the world's least-studied and most inaccessible wetland systems, this study advances understanding of human adaptation to flood risk and offers context-specific insights for resilience planning in the Sudd and other climate-vulnerable wetlands.

Keywords Sudd Wetland · Flood Risk · Human Adaptation · Flood-Induced Mobility · Socio-hydrological System · Climate Resilience

Introduction

About 1.81 billion people, 23% of the world population, are directly exposed to flood depths greater than 0.15 m in a 1-in-100-year flood event (Rentschler et al. 2022), posing significant risk to lives and livelihoods. Of these exposed populations, 89% live in low-and middle-income countries. Many developing countries are ill equipped to deal with the consequences of flooding, including population movements that occur where climate hazards interact with high vulnerability and low adaptive capacity (a broader socio-hydrological process that enables long-term resilience)

Communicated by David Lopez-Carr

✉ Deng Majok Chol
deng.chol@ouce.ox.ac.uk; dengmchol@yahoo.com

[1] Environment Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK

[2] Sociology and Environmental Studies, The University of North Carolina Greensboro, Greensboro, USA

(Adger et al. 2018; Shweta et al. 2017; McLeman and Hunter 2010). South Sudan, in eastern central Africa, is one of the world's most fragile states and one of the least developed countries in the world (UNEP, 2018). In 2022, South Sudan was ranked the world's most vulnerable country to climate change with the lowest level of coping capacity (the ability to manage immediate impacts of hazards such as extreme flooding) (De Groeve et al. 2014; Kose 2024; Alfieri et al. 2018). The country is a global hotspot of flood risk, ranking 7th in the world for share of total country population exposed to river floods, and the situation is expected to worsen under climate change (Borgomeo et.al 2023).

The Sudd region is a vast depression in the middle of South Sudan that includes savanna and extensive floodplains around the Sudd's permanent wetlands and seasonal swamps (Fig. 1). The Sudd's ecosystem services are indispensable for biodiversity; for example, it hosts the largest land mammal migration on Earth, with an estimated six million antelope migrating across the country each year (National Geographic 2024). The Sudd is vital for livelihoods and wellbeing of local communities (Howell 1983; Howell et al. 1988; Evans-Pritchard 1940; Johnson and Anderson 1988). However, water insecurity is an existential threat to South Sudan (Borgomeo et al. 2023; Kose 2024). The communities in the Sudd region are particularly reliant on natural resources (Kose 2024; Howell et al. 1988) for their livelihoods. Approximately 86% of rural households rely on rainfed agriculture and animal husbandry as their main source of income (UNEP, 2018).

The impacts of extreme flooding events since 2019 have significantly altered habitats by causing erosion of riverbanks, depositing sediment that smothered aquatic life, displacing humans and wildlife, altering water flow, and reshaping landscapes. The higher flood regime has led to a change in the composition and availability of habitats for humans and various other species depending on the ecosystem affected. The 2019–2022 floods were reported as the most devastating since the early 1960 s, impacting around one million people and displacing more than 300,000 (Borgomeo et al. 2023). The intersection of armed conflict, which has been ongoing since 2013, and recent

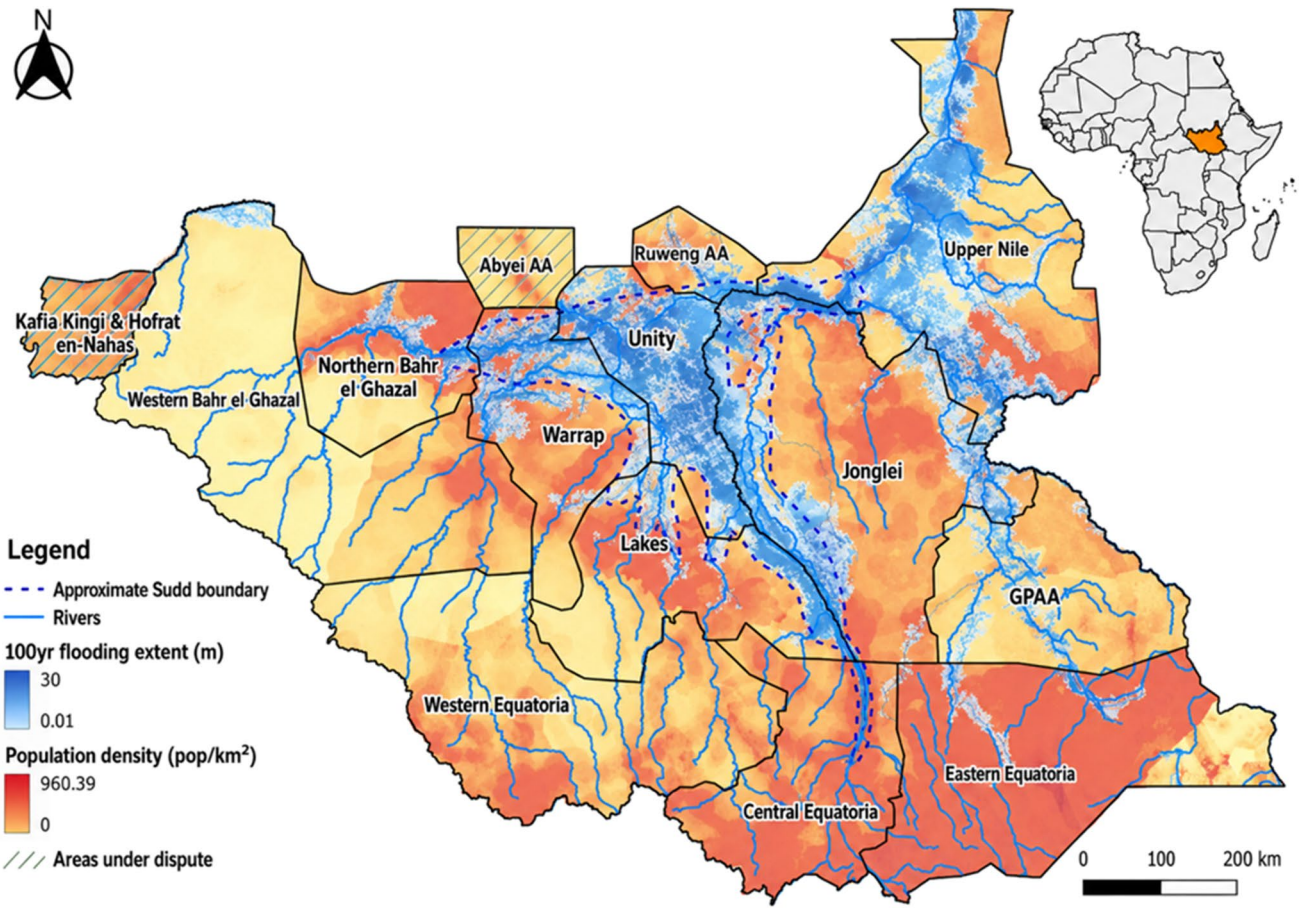


Fig. 1 Map of the approximate Sudd boundary in the context of population density (for the year 2020 from WorldPop (Tatem 2017)) and the 100-year flood depth GLOFRIS flood model (Ward et al. 2013). Note, there is no official definition of the boundary of the Sudd; it has been delineated based on flood extents and a compilation of existing (differing) delineations (Chol et al. 2026)

historic flooding has exceeded the coping capacities of the fragile Sudd population.

Considering the causes of human migration are conceptually and empirically multidimensional and multifactorial (Haasnoot et al. 2013; Falco et al. 2019; Thiede et al. 2016; Chung et al. 2022; Agnew et al. n.d.; Kroll-Smith and Leon-Corwin 2023), this paper focuses on extreme flood-induced migration by detecting and tracking the impacts of flooding on the lives of people affected through various flood impact channels. These flood impact channels refer to multiple pathways through which flood affects communities, including direct physical impacts (loss of land, infrastructure, and settlements), livelihood impacts (agriculture, livestock, fishing), health impacts, and indirect social impacts such as displacement, conflict, and changes in social systems. Flood-induced migration patterns are revealed through empirical studies conducted in the Sudd region across a wide range of communities and populations across the states in the Sudd floodplains. The field research used focus group discussions (FGD) and semi-structured interviews to produce primary data, and participatory qualitative mapping approaches to develop a spatially explicit understanding of people's mobility in response to flooding.

Recognizing the interconnectedness of human and water systems in the Sudd, a socio-hydrological approach (Blair and Buytaert 2016; Feng et al. 2017; Hu et al. 2018; Pouladi et al. 2020) is applied that considers both social and hydrological processes. The study assesses how social and ecological factors contribute to flood vulnerability and risk, such as population density, poverty, ecosystem degradation, and land use patterns. A spatio-temporal socio-hydrological framework conceptualizes flood adaptation as a dynamic process operating across interconnected household, community, regional, and national scales over time. The framework advances understanding of how hydrological change, migration, governance, and social transformation shape adaptation pathways in the Sudd and other climate-sensitive wetland systems. The study addresses the following questions that capture both the past and contemporary flood experiences and perspectives:

1. How does extreme flooding influence migration in the Sudd region?
2. How is the perception of the changing frequency and severity of flooding shaping migration patterns and preferences in the Sudd region?
3. How do changes in migration patterns vary across different communities or livelihood groups as the severity of extreme impacts increases?
4. How are flood, migration, conflict, and social systems interconnected in the Sudd region?

The hydrology of the Sudd within the Nile River system has been studied by numerous investigators (such as Petersen 2008; Sutcliffe and Brown 2018; Persico et al. n.d.; Sutcliffe and Parks, 1999; Di Vittorio and Georgakakos 2021; Johnson 1992; Johnson 2019; Rebelo et al. 2012; Kose 2024; Sutcliffe et al. 1989). However, there is currently no research on the dynamics of adaptation to flooding in the Sudd, which is hindering policy responses and adaptation at a range of scales. Conducting research on migration patterns in this region is often extremely difficult as these lands are among the world's most remote places. The region has been inaccessible for more than half a century due to dense vegetation, challenging terrain, and multifaceted conflict including the longest war in Africa (Sudanese civil war from 1983 to 2005) and South Sudanese civil war (2013–2018). This study is the first systematic assessment of the dynamic interactions between population and flooding, and has the potential to inform communities' resilience plans and flood risk management planning at the community, state, Sudd region and national levels.

Study area

Geography, climate, and environment

At the subnational level, South Sudan is divided into states or administrative areas, which are comprised of local counties. For this study, the Sudd region is defined as the administrative boundaries within and around the Sudd permanent wetland (Fig. 1), including a west-central area that is centered at the juncture of Bahr el Jebel Sub-basin southward, Sabot Sub-basin in the northeast, and Bahr el Ghazal in the northwest. The Sudd region covers the Central Equatoria State and Eastern Equatoria State in the south; Upper Nile State, Jonglei State, and Greater Pibor Administrative Area (GPAA) in the Sudd eastern floodplain; the states of Warrap, Unity, and Lakes in the Sudd western floodplain; and Ruweng Administrative Area in the north. The fieldwork for this study was conducted in portions of the Jonglei, Unity, Upper Nile, Warrap, Lakes, and Central Equatoria states. These states were selected because they are in unrestricted flooding zones, which are areas with a high-risk of flooding and limited protective man-made structures.

The Sudd has a unique geography that includes plains, plateaus, swamps, and forests. The Sudd region generally has two distinct weather systems. The long rainy season typically lasts from June to October, while the dry season extends from November to May. The rainy season differs by location. As the World Bank Climate portal records show, the lowland areas of Eastern Equatoria, Jonglei, the Upper Nile, and the Bahr el Ghazal region receive annual rainfall

between 700 and 1300 mm. The heaviest rainfall occurs in the southern upland areas and decreases toward the north. Western Equatoria and highland parts of Eastern Equatoria receive between 1200 and 2200 mm of rainfall annually (Lukwasa 2022; Climate Change Knowledge Portal, World Bank).

Changes in the Sudd hydrology

A significant change in the hydrological regime of the Sudd occurred when the level of Lake Victoria rose by over 2 m from 1961 to 1964 due to exceptionally high rainfall and resulted in a rise in the inflow to the Sudd at Mongalla (Mangalla) and a large increase in permanent and seasonal inundation (Sutcliffe and Brown 2018). Prior to the fieldwork conducted in this research, Lake Victoria experienced record-breaking elevations from 2019 to 2022 resulting in severe downstream flooding. Furthermore, after the fieldwork was completed, Lake Victoria reached its highest recorded water levels (Fig. 2), reaching 1136.79 masl in May 2024 (Dahiti- Schwatke et al 2015). The lake levels were extraordinarily high due to heavy rainfall and infrastructural changes in the dam management near Jinja. Water levels in the Jinja Dam nearly exceeded capacity in 2024, prompting the Ugandan Government to release 2600 m^3/s of water downstream into South Sudan (Kothari 2024). However, the specific impact of dam operations in managing water levels is a point of contention. These high lake levels are associated with the largest flood extent in the Sudd in recent memory.

Seasonal migration (transhumance) in the Sudd region

The seasonal movement of pastoralists and their herds—academically referred to as transhumance—is a traditional strategy of animal farmers in drylands around the globe to cope with climate variability and water scarcity (Piemontese et al. 2024; Krätli 2015; Chung et al. 2022; Caretta et al. 2023). Among communities in the Sudd, the practice is locally understood through culturally specific terms and customary systems of livestock movement rather than necessarily through the term "transhumance" itself. In the Sudd region, such mobility is a strategy that has been practiced by the agro-pastoral communities of the Shilluk, Dinka,

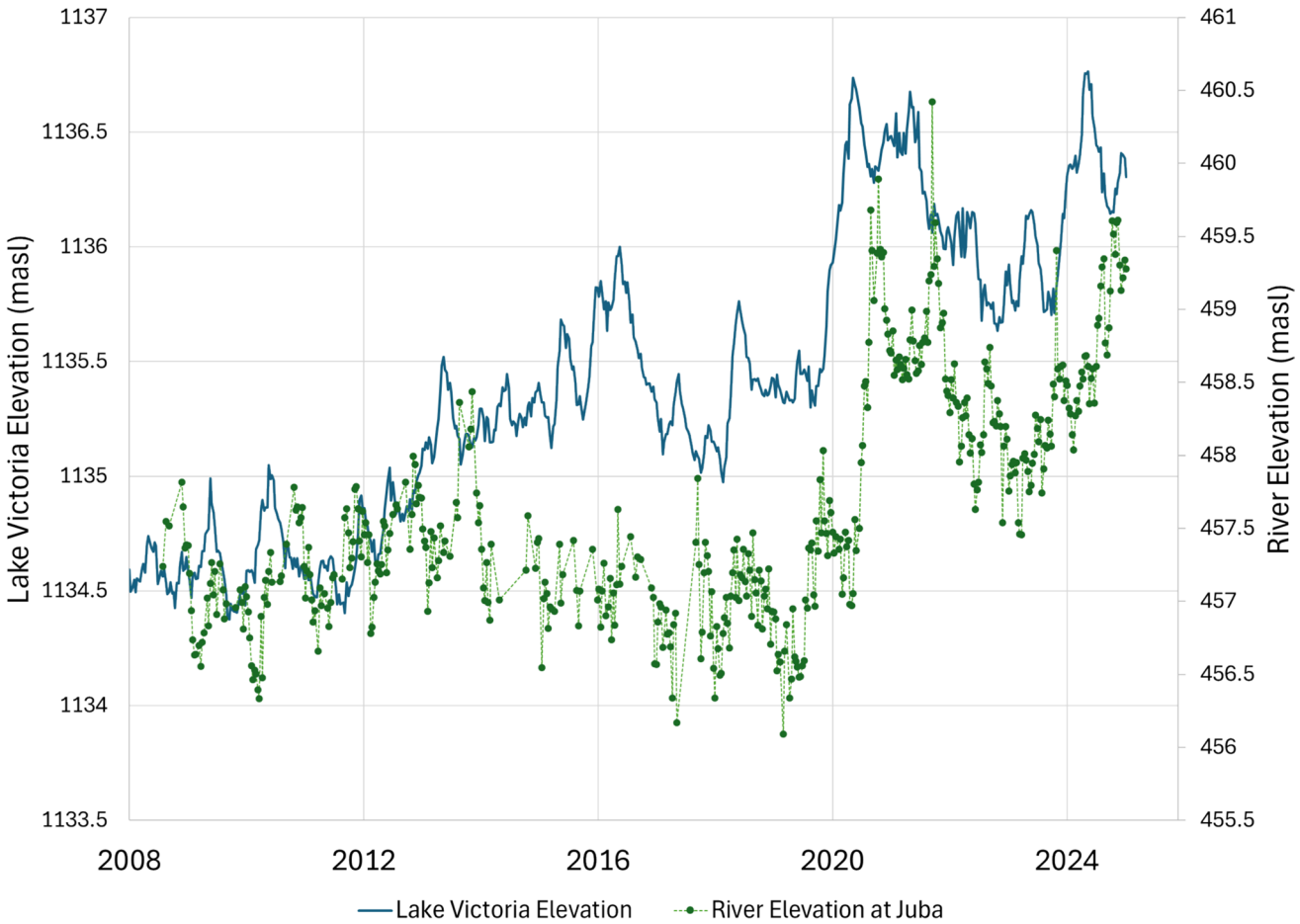


Fig. 2 Comparing Lake Victoria elevation and River Nile elevation at Juba (data source: Dahiti-Schwatke et al 2015)

Nuer, Mandari, Murle, Anuak, and Jie people for a long time along the Sudd Nile. These communities share a history of seasonal migration as they navigate the impacts of climate variability, following water movements and vegetation growth cycles (Di Vitorio and Georgakakoas 2021) during the wet and dry season to ensure the health of their livestock and dairy products. Such transhumance, or the movement of livestock, is based on a seasonal cycle that can be divided quarterly into the dry season, the inter-season, the wet season, and the recession season (Fig. 3).

Figure 3 establishes a baseline of normal seasonal mobility, which is essential to demonstrate how recent extreme floods have disrupted traditional systems. The system of social and governance institutions of annual transhumance in the Sudd region is intergenerational, having been passed down through cultural practices from one generation to another. The system is often learned at an appropriate young age (from 12 to 17 years), instilling the value and memory of timing, associated social activities, and routes of annual transhumance as dedicated by the hydrology of the Sudd Nile.

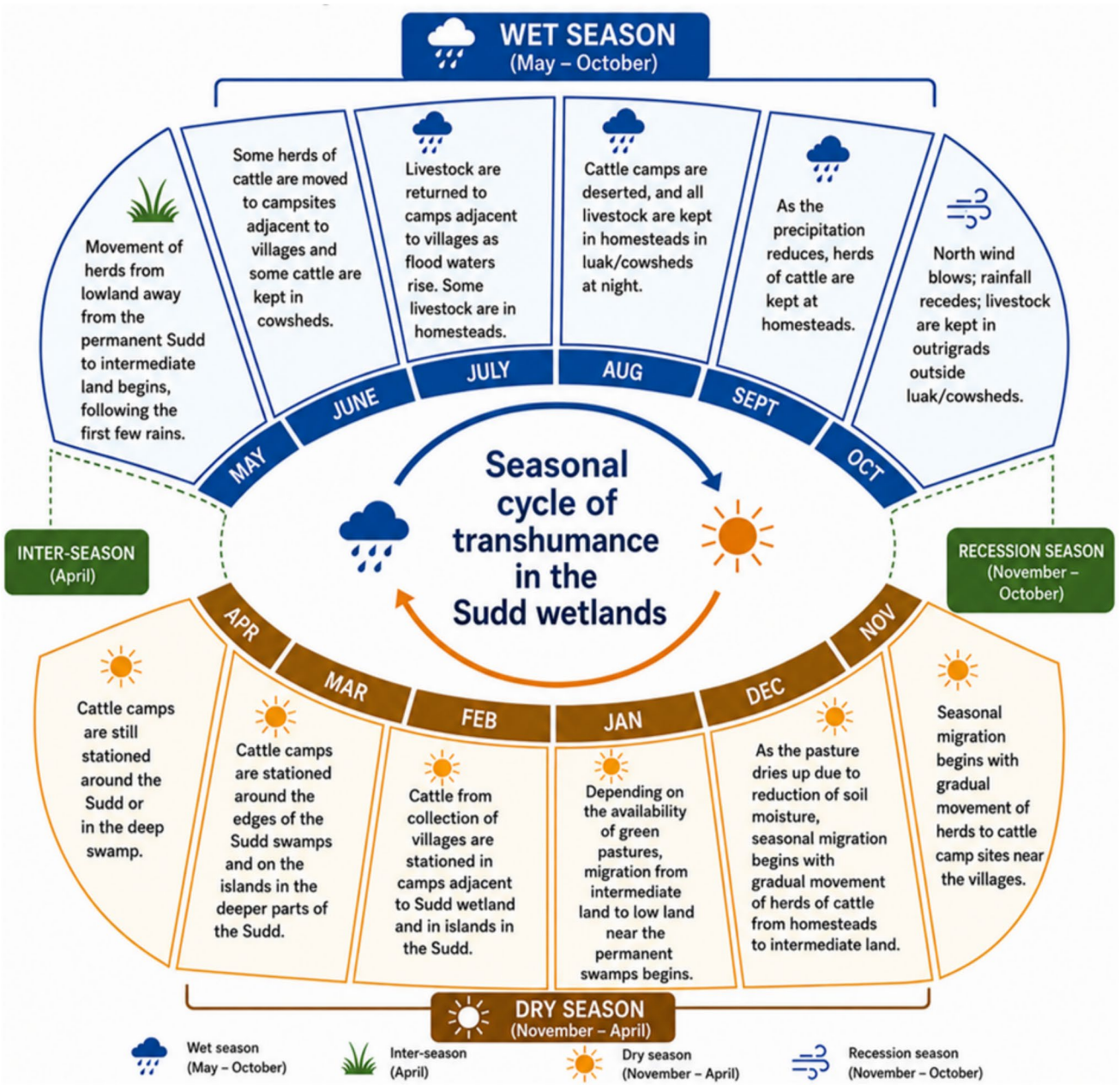


Fig. 3 Seasonal cycle of annual transhumance in pastoral livelihoods of the Sudd Region [adapted from de Mabior (1981)]

Data and methods

The fieldwork presented in this section was designed to investigate the dynamic interactions between hydrological variability, human exposure, and adaptation responses in the Sudd wetland socio-hydrological system. This fieldwork was developed to examine the processes underlying those patterns: how communities experience changing flood regimes, interpret environmental risks, and make decisions regarding mobility, livelihoods, and settlement. The fieldwork therefore provided an empirical basis for moving beyond a hazard-exposure perspective, towards an understanding of flood adaptation as a dynamic, socially embedded process. Data collection took place between February and June 2024 across selected locations within the Sudd region of South Sudan. The fieldwork design was informed by the concept of dynamic adaptation, which conceptualizes adaptation not as a single adjustment to environmental change, but as an evolving process involving repeated decision-making under changing ecological and social conditions. A mixed-method approach was adopted because conventional quantitative modeling approaches alone face important limitations in the Sudd context. Quantitative models are constrained by the scarcity of reliable hydrological, demographic, and socio-economic datasets; the challenges of accurately representing complex wetland flood dynamics; and their limited ability to capture the social, cultural, and perceptual dimensions that shape human responses to environmental change (Chol et al. 2026). Qualitative methods provide a more appropriate ap

proach for investigating adaptation processes in this setting by capturing lived experiences, indigenous knowledge, and community interpretations of flood risk. They also allow examination of the non-linear, socially embedded, and context-specific pathways through which households and communities adapt to changing flood conditions.

Field sites

We conducted field visits to the environments and contexts of the flood-affected populations, knowing this approach encourages respondents to speak more freely and creates the opportunity for community participatory mapping. The selection of field locations followed a multisource evidence approach. We triangulated data sources from multiple, diverse sources, including reference plots of past flood research transcriptions (Johnson 1992), successive records of data from the International Organization of Migration (IOM) displacement tracking matrix, stream inflow at Mongalla (Mangalla) from 1820 to 1983 (Hurst 1933 and subsequent supplements), and results of the population exposure to flood risk in the Sudd region (Chol et al. 2026).

Five predominant states of the Sudd region face the most profound flood hazards: Jonglei, Unity, Upper Nile, Warrap, and Lakes states. The fieldwork covered all these areas (Fig. 4). Juba, the Capital City, was selected as an adjacent location for expediency of interactions with various respondents at the Sudd region and national levels.

The field sites included cattle camps, farms, fishing camps, Internally Displaced Persons (IDPs) camps, villages, Protection of Civilians (PoC) sites, and towns. These sites were selected because they experienced large flood hazard and population exposure (Chol et al. 2026) and were experiencing ongoing (2019–2024) flood disasters according to reports by the South Sudan Government, UN Office for the Coordination of Humanitarian Affairs (UNOCHA), and IOM. These sites (Fig. 4) are representative of the Sudd geography and its populations. The detailed administrative structure of each of the counties visited is included in the supplementary information.

The fieldwork combined qualitative data collection methods, including focus group discussions (FGDs), semi-structured interviews, and walking interviews, with direct field observations undertaken through boat surveys, aerial surveys, vehicle transects, and walking observations across flood-affected landscapes. Although interviews and FGDs were conducted in most of the mapped locations, some sites were included primarily because they provided important contextual information on flood dynamics, settlement patterns, mobility practices, and human–environment interactions within the Sudd. The combination of these approaches enabled the study to capture both the lived experiences of flood-affected communities and the broader spatial and ecological characteristics of the flood landscape.

Data and field research methods

We collected the field data from 18 February to 4 June 2024 using various methods (Table 1). interviews. The study was conducted with participants who were selected from different communities or livelihood groups including pastoralists, subsistence farmers, fishers, and IDPs who depend on UN food aid. While we differentiate between community groups for analytical purposes, in many instances, populations that were assessed were either displaced, or in their homes, or in transitional locations such as the cattle camps. We classified community groups by their "administrative units," which was where they consider their natural homes. Some of the FGDs and semi-structured interviews were conducted with water sector practitioners from the states and administrative areas, as well as with community key informants (experts) from the Sudd region.

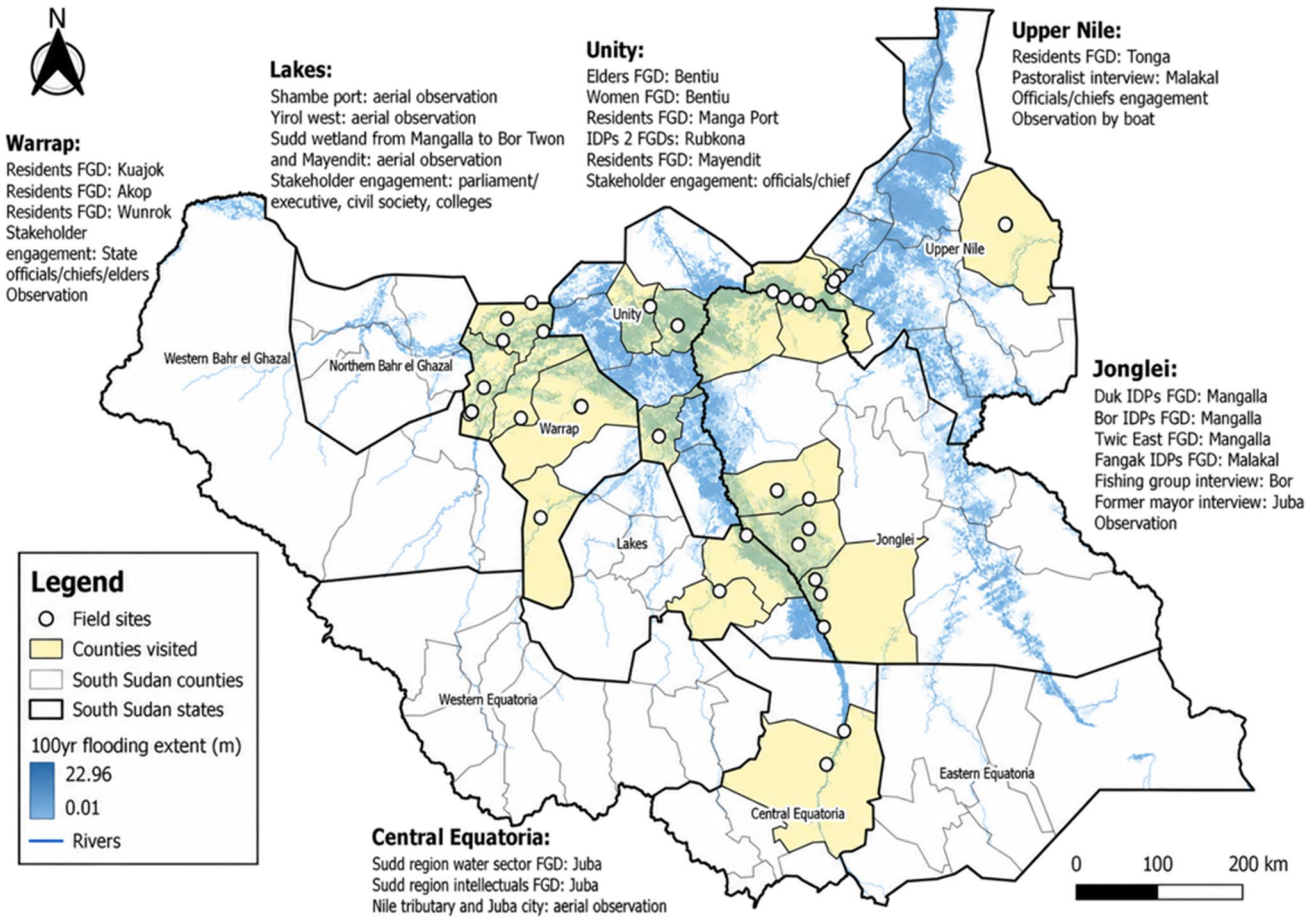


Fig. 4 Fieldwork locations visited in the Sudd region for this study, including sites where focus group discussions, interviews, and direct field observations were conducted (based on GPS coordinates collected during fieldwork). The 100-year flood extent from the global GLOFRIS flood model (Ward et al. 2013)

Table 1 Data collection and analysis methods

Methods of data collection	Data and materials	Data analysis	Analysis tool
Focus group discussions	Group discussions narrative data	Thematic analysis	The NVivo tool, a qualitative data analysis (QDA) computer software
Semi-structured interviews	Interview data	Narrative analysis	
Qualitative mobility mapping	Spatial information	Spatial data analysis	
Observation and documentation	Photos/videos, field notes	Video/photo analysis Fieldnote analysis	

Focus group discussions and semi-structured interviews

Focus group discussions were used to generate collective perspectives and examine how flood impacts are understood within different livelihood communities. Groups were organized around shared experiences, including farmers, pastoralists, fishing communities, and displaced populations. Each discussion focused on themes including flood impacts, livelihood disruption, mobility strategies, settlement change, indigenous knowledge, and future adaptation choices. The group format was particularly valuable because it enabled participants to discuss, challenge, and refine each other's experiences, revealing shared understandings as well as differences within communities.

Semi-structured interviews provided a complementary approach by allowing deeper exploration of individual experiences and historical narratives. The flexible interview structure enabled participants to describe flood experiences in their own terms while allowing the researcher to explore specific issues related to migration decisions, risk perception, and adaptation pathways.

Taking a community-level approach simplifies the sampling process, as the study focuses on community representatives—chiefs, youth, women, and elders. Participants for the community-level FGDs were identified and recruited by the administrators of respective IDP camps, and by the chiefs and local officials for those who were still in their villages. The lead researcher provided overall leadership for the fieldwork and led all interviews and focus group discussions using structured research questions. Research assistants and local community leaders supported participant recruitment and identified individuals representing diverse social groups, including elders, women, and youth. Recruitment followed clear instructions from the research team to ensure diversity in age, gender, livelihoods, and geographic representation. Research assistants also provided simultaneous translation during interviews and focus group discussions where required. The participants were group representatives of their counties in Jonglei State, Unity State, Upper Nile, and Warrap State. Most of the group discussions and interviews were conducted in local languages (eight in Dinka, seven in Nuer, and one in Shilluk) and the audio recordings were translated to English. Two FGDs were administered in English. There was a total of 216 participants in the field study. The FGDs were made up of members of different age groups (18–80) to leverage the depth and breadth of intergenerational connection in the context of human-flood lived experiences. In total, 13 community-level FGDs were conducted, including 184 respondents. In addition to the FGDs, two semi-structured interviews were also undertaken. A series of individual walking interviews were done with five fishermen, three of whom were South Sudanese nationals, and two foreign nationals from Kenya and the Democratic Republic of the Congo (DRC), at Aduar fishing hub in Bor County, Jonglei State. The Aduar site houses over 180 individual fishermen and fisherwomen who represent five countries including DRC, Kenya, Uganda, Sudan, Somalia, and South Sudan. The other interview was conducted with a former mayor of Bor Town, the capital city of Jonglei State.

Lastly, two additional FGDs were undertaken, one with 13 community key informants and the other with 13 water sector experts at the national level. The recruitment of 13 community key informants was based on the snowballing sampling method, a technique in which participants are asked to identify other potential respondents, considering their historical and/or professional knowledge about their communities and flooding. These community key informants represented five states in the Sudd region, Jonglei, Lakes, Warrap, Unity, Upper, and Ruweng Administrative Area, and were either former or current local administrators, NGO workers, staff members of relevant institutions, community leaders, or business members. The other FGD was conducted with the other 13 respondents, who were water sector experts and were recruited by the National Ministry of Water Resources and Irrigation, and they represented various state line ministries, including the ones responsible for water resources and irrigation, environment and forestry, agriculture, and urban planning. Some of the FGD and interview sample questions are outlined below, but the full list of the fieldwork questions and breakdown of the data by ages, genders, and locations of the participants can be found in the supplementary material.

The FGDs and interviews also sought to collect flood memories among the communities in the Sudd region from 1943 to 2023, to put recent events in historical perspective. This period is chosen because it covers the memories of three to four generations aged 18 to 80 years old. Importantly, this period covers the 1990s, which encompasses the last phase of the peace negotiation between factions in the Sudan Government and rebel group from Southern Sudan (now South Sudan), and the eventual signing of the Comprehensive Peace Agreement (2005), which was followed by the return of populations from IDP and refugee camps to their respective villages. The flood memories also cover the full history of South Sudan as an independent nation (since 2011). The successive generational age groups in the study are expected to have shared memories of flood events that occurred over the last 80 years (Fig. 5).

While there is inherent uncertainty in most memories, particularly those reaching back 50 to 80 years, the use of memory-based flood reconstruction (1943–2023) is justified by the nature of knowledge systems in the Sudd, where environmental knowledge is intergenerational and culturally embedded through oral traditions, songs, naming systems, and shared community narratives. For example, names are recycled from one generation to the other, so that living persons are, in considering their names, the evidence of past flood events. The collective memories of such key events were also captured in songs and enchantments that survived the test of time to the current generation that has recorded them using twenty-first century technology, making such knowledge available to future generations. Therefore, memory-based reconstruction is used to complement, rather than replace, hydrological observations and other empirical datasets.

Qualitative mobility mapping

A distinctive element of the field design was the incorporation of participatory mapping to examine the spatial dimensions of flood-induced human mobility. Because mobility is central to life in the Sudd, participants were invited to describe and map historical and contemporary movement routes, seasonal migration pathways, and changes in mobility patterns associated with flooding. Group discussions and collaborative mapping sessions were held, where participants across different community groups drew, sketched, and



Fig. 5 Focus group discussions in Bentiu, Unity State with **A** IDP women, including three elderly aged between 67 and 73, and **B** five elderly IDP men, aged between 83 and 89 (photos were taken with the participants' permission)

annotated locations on maps to represent their movements and experiences. Walking interviews were included as part of the semi-structured interviews and were conducted with participants to gain deeper insights into their spatial experiences and interactions with their environments. The participants were also asked to describe and draw changes in seasonal/transhumance routes in relation to their perception of changes in the intensity and frequency of flooding events. This allowed us to spatially examine the differences between the impacts of seasonal flood-induced migration directions versus those resulting from a new higher flood regime and differentiating migration patterns that are attributable to dynamics emanating from factors other than flooding. The resulting qualitative maps provided a means of interpreting human mobility not simply as displacement, but as a complex adaptation process shaped by ecological conditions, livelihoods, and social institutions.

Ethical considerations and research ethics processes

Ethical considerations were integral to the design, implementation, and interpretation of this research, particularly given that the study involved engagement with flood-affected communities living within the socially, environmentally, and politically complex context of the Sudd wetland region of South Sudan. The research involved collecting lived experiences, local knowledge, and personal narratives related to flooding, displacement, livelihood disruption, and adaptation, requiring careful attention to participant dignity, safety, confidentiality, and the potential impacts of participation. Prior to commencing fieldwork, ethical approval was obtained through the University of Oxford Central University Research Ethics Committee (CUREC) under Ethics Approval Reference: SOGE C1A 24 01, and all field activities were conducted in accordance with the approved ethical protocol and University guidance for research involving human participants.

Data analysis

The fieldwork design incorporated an analytical strategy that linked data collection directly to the research objectives. Interview and focus group data were transcribed, coded, and analyzed thematically to identify recurring patterns relating to flood impacts, adaptation strategies, migration decisions, and changing relationships between communities and the wetland environment. Narrative analysis was also applied to understand how participants constructed explanations of environmental change and mobility through personal and collective histories.

Structured components of interviews provided additional comparative information on migration drivers, adaptation preferences, and perceived changes in flood conditions. Findings from interviews, focus groups, participatory mapping, and observations were triangulated to strengthen interpretation and identify areas of convergence or divergence between different sources of evidence. Since the field data is large in quantity, encompassing a wide range of variables and hundreds of participants, we selected NVivo to manage and aid our analysis of field data. After the translation of all the transcripts from different South Sudanese ethnic languages to English, we created 18 documents (i.e., one document per FGD/interview) of all field data and imported them into NVivo.

After transcribing the fieldwork data, we use thematic analysis within NVivo to understand participants' lived experiences, as well as their views or stories about flooding and its impacts. We use this approach to assess their indigenous hydrological knowledge, values, and beliefs, and assess how they relate to social systems vis-à-vis the impacts of flooding. Using a codebook approach, we created the initial codes (i.e., predetermined themes from the transcripts), and iteratively categorized the qualitative data into themes (Fig. 6).

The analysis for this study is based principally on seven migration-related themes: 1, 3, 4, 5, 6, 9, and 10. The coding of themes was an iterative process, with themes added

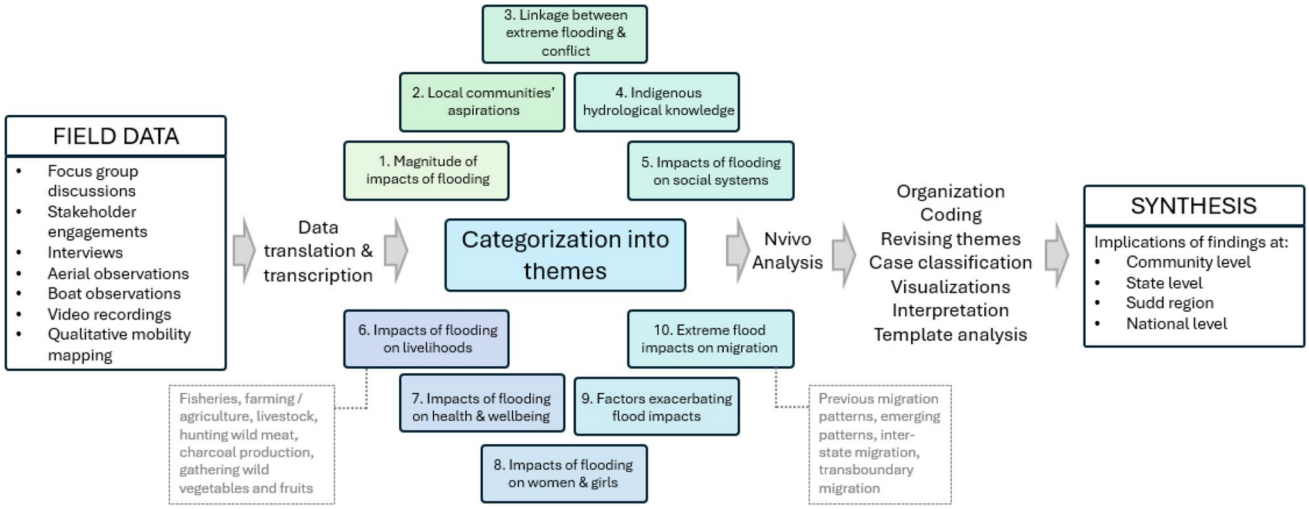


Fig. 6 Analytical framework illustrating the qualitative data analysis process used to develop ten major themes from field data through transcription, coding, thematic analysis, and synthesis. The dotted boxes present illustrative examples of the specific livelihood activities and migration patterns discussed by participants within themes 6 (impacts of flooding on livelihoods) and 10 (extreme flood impacts on migration), respectively, and are not separate analytical themes

and revised as they emerged in the captured data. To ensure the analysis is not sensitive to the first NVivo analysis project, each of the 18 projects has its own final code structure, which can then be compared through the code references generated for each of the 10 themes. By assessing the number of occurrences of themes, we can obtain insights into their relative importance (e.g., under Theme 10, we can quantify how many references were made to previous migration patterns versus the more recently emerging patterns, and the scales of migration routes to understand the most prominent migration patterns). Reports of the analysis were produced in various quantitative formats, such as tables of coding structures, maps, hierarchy charts, and word frequency tests. By combining hydrological understanding with community-based evidence, the research examined not only where flood risks occur, but how those risks are experienced, interpreted, and transformed into adaptive decisions by affected populations.

Uncertainties and assumptions in the methodology

While we aimed for diversity of participants, men between the ages of 40 and 60 comprised most of the participants. Considering cultural dynamics, young people under the age of 25 and women were less willing to volunteer for the study. In South Sudanese cultures, the elders' veneration is deeply ingrained, with younger generations showing profound respect and deference to their elders. Younger participants, particularly girls, were shy and spoke less during the FGDs and structured interviews. Dominance bias, particularly the influence of elders or men who may hold greater social authority, was mitigated through diverse participant sampling and the use of multiple FGDs conducted across different locations to capture a range of perspectives.

Although memory-based accounts contain uncertainties, collective recall is often socially validated within communities and provides valuable temporal depth that is unavailable from limited instrumental records. Recall bias was addressed by focusing on collective intergenerational memory rather than relying solely on individual recollections. Given these considerations, the findings are presented as interpretive and indicative rather than statistically representative.

Translation from Dinka, Nuer, and Shilluk into English may introduce the risk of losing culturally specific meanings, metaphors, and contextual expressions, a limitation inherent in multilingual qualitative research. To mitigate this risk, translation was undertaken carefully with the support of native speakers and bilingual translators familiar with local cultural contexts who conducted or assisted with interviews. Additional measures included cross-checking translations during transcription, retaining original phrasing where translation could alter meaning, and validating interpretations against fieldwork notes and researcher observations.

As with all survey data, the findings are static in time and space, although the dynamics assessed are constantly changing. Questions such as "what is your current livelihood?" capture current livelihood-generating activities, and do not assess whether livelihood activities have changed from the past. Thus, the themes that have come out of the NVivo thematic analysis represent the current important issues for the communities, in the context of flooding. Finally, drawing quantitative conclusions from qualitative data also has its limitations. For instance, counting word references that are generated under each theme could give a false quantification

of significance; thus, in this study, we emphasize that such quantitative findings are useful in providing an indication of the themes that participants deem worthy of discussion during the time of research. Finally, the analysis of migratory behavior in response to the impacts of extreme flooding only investigates historically observed relationships, which are not necessarily reflective of future migration patterns in the Sudd region.

Results

Communities across the Sudd demonstrated the presence of indigenous hydrological knowledge embedded in long-standing cultural practices, observations, and interpretations of environmental changes. This knowledge was expressed through the expertise of traditional leaders, including rainmakers, and community members who interpret climatic and hydrological signals based on changes in weather conditions, river levels, wind patterns, animal behavior, and ecological processes. Although largely informal, diverse, and sometimes associated with uncertainty and differing interpretations, this knowledge system represents an accumulated understanding of local environmental dynamics that has been transmitted across generations and used to guide decisions related to livelihoods, particularly livestock management and adaptation to changing flood conditions. A respondent described indigenous hydrological knowledge as follows:

> Local communities have sophisticated understanding of the science of the climate they live in. Everything that affected the health of their cattle was very important to them. They had learned the patterns of changes. That knowledge was established and handed down from generation to generation. (A policy maker, from Jonglei State)

Given the highly disruptive and relatively recent events during the flood season of 2019–2022, the impacts of these events were foremost in this indigenous understanding of flooding, captured in participants' responses. This results section is structured according to the four research questions. The section addresses flood impacts; the section examines how perceived changes in flood regimes influence migration; the section explores differences among communities and livelihood groups; and the section examines interactions between flooding, migration, conflict, and social systems.

Impacts of extreme flooding in the Sudd region

The results reveal that recent flooding in the Sudd has become more severe (2019–2022) relative to the 1961–1964 flood that marked changes in the channels through the Sudd swamps. This shift in the typical pattern of the flood regime, characterized by an increase in magnitude, manifests highly disruptive impacts for the local communities and population. Participants' accounts of impacts of these high-magnitude flood events reveal existential threats, including stark references to numerous losses of lives, particularly among the elderly, women, people with disabilities, and children. In the words of one who has lived through severe flooding:

> This one (2019-2022 flood event) is the third major flood, with greater magnitude. We, the Nuer elders in Bentiu, call it 'Baap' in the Nuer language, a sweeping force of nature that swept away people, forests, settlements, buildings, and roads. (89-year-old man, Bentiu, Unity State)

Similarly, Apuk Padioc Dinka in the Tonj North County (Warrap State) named the 2019–2022 flood "Riem" in the Dinka language, a massive force that indiscriminately destroyed everything. Field observations across the Sudd region corroborate participants' accounts of a higher flood regime. As stated by villagers, flood water levels (Fig. 7) have far exceeded previous levels and have not receded in five years in most of the fieldwork sites across Unity State, Jonglei State, Upper Nile, and Warrap State. Five consecutive seasons of destruction of traditional livelihood systems, such as farming and cattle rearing, have resulted in new migration patterns (Fig. 8).

Considering these communities largely derive their living from land, waterlogged fields rendered farming impossible for five subsequent seasons (from 2019 to 2022). One respondent describes the impacts of extreme flooding on livelihoods as:



Fig. 7 **A** Bor Town submerged in the flood and **B** a group of youths building a handmade dike (photos taken by M. Martin Majier, December 2020, Jonglei State)

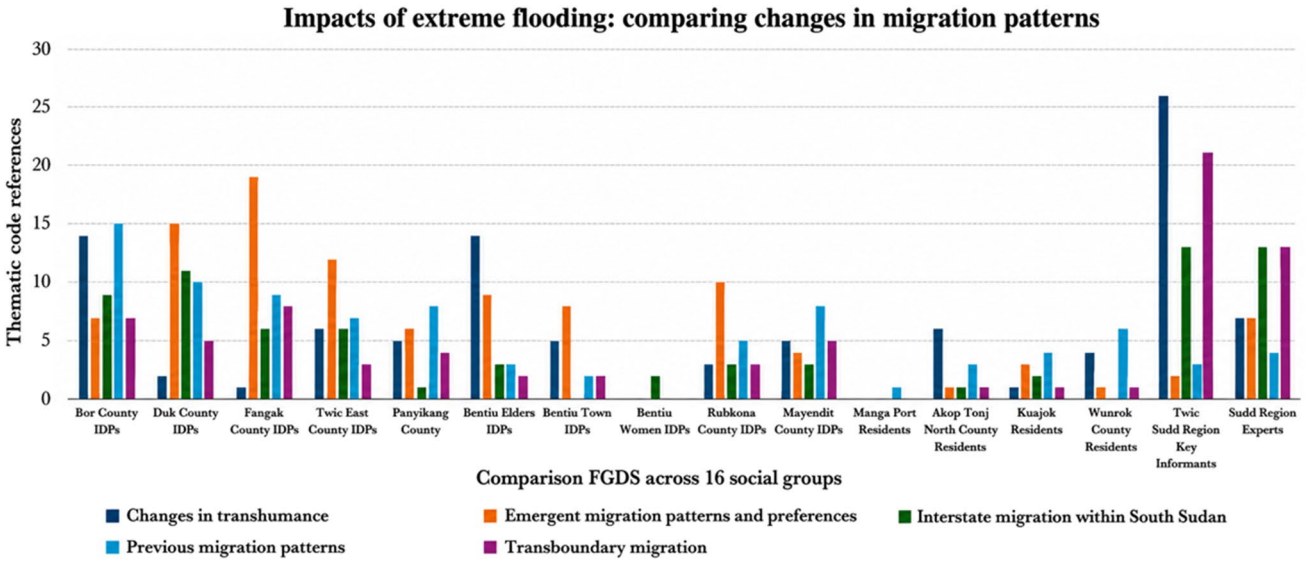


Fig. 8 Comparing migration patterns across 16 different community groups. These response categories are related to five subthemes (graph legend) of migration. "Previous migration patterns" refers to similar routes and patterns taken now as during past flood events; "emergent migration patterns and preferences" refers to new patterns taken during the 2019–2022 flood; "changes in transhumance" corresponds to new patterns in seasonal migration of livestock; "transboundary migration" refers to migration to neighboring countries; and "interstate migration within South Sudan" refers to migration from one state to another

> The flood has had destructive impacts on major sources of our livelihoods. The flood has impeded farming, including the destruction of crops that were planted. The impacts of flooding led to the outbreak of cattle diseases and caused migration of wildlife away from human populations, thereby denying opportunity for wild meat. (An elderly man, Akop, Payam, Tonj North, Warrap State)

Despite the severe disruptions caused by extreme flooding in the Sudd, flooding has also generated alternative livelihood opportunities that support local resilience. The same floodwaters that undermine land-based livelihoods create productive aquatic environments, increasing access to resources such as fish and water lilies.

How perceptions of changes in the flooding regime influence migration patterns

Local communities across the Sudd demonstrated strong awareness of emerging changes in migration patterns and preferences in response to extreme flooding. Pastoralists reported shifts from established transhumance routes toward new movement patterns shaped by expanded flood extents and changing environmental conditions. At the broader population level, the scale of recent floods established a new reference point for extreme events, surpassing previous experiences remembered from events such as the 1960 s floods. These changes were influenced not only by flooding but also by historical and contemporary factors, including inter-community conflicts, the 2013 civil war, changing perceptions of government protection, and the presence of humanitarian actors such as the UN, which were absent during earlier flood events. These changes have led to longer migratory patterns and movements among both the pastoralists and the wider population. About 82% of participants described these migratory patterns. The population's understanding of increased flood risks is affecting migratory patterns, including a surge in interstate (from one state to another within South Sudan) and transboundary (from South Sudan to other countries) migration. In the words of a former mayor:

> Initially, the rural populations around Bor Town were flooded, and they moved to the center of the town. Then when the town was flooded, these people migrated to Mongalla, Juba, and Nimule in Central Equatoria. However, when these IDPs did not find any suitable places to regain their livelihoods and access services, they proceeded to the refugee camps in Uganda and Kenya. (A former mayor of Bor Town, Jonglei State)

The results indicate that half a decade of successive flooding and persistent waterlogged fields have changed the temporal patterns of transhumance (seasonal livestock migration). The vast majority (93%) of respondents across all counties reported that annual transhumance cycles were not feasible due to the submergence of traditional routes and lack of dry land. Such sudden changes in transhumance systems among the pastoralists from long-established to

emergent patterns, routes, and preferences were described in detail in response to the impacts of high floodwaters across the Sudd, as highlighted by this key informant:

> Upland migration or inland migration has increased as people with their cattle migrate away from the expansive lowlands. The normal migration patterns were towards lowland areas during the dry season. But because of abnormal or extreme flooding, migration routes are being pushed upland. (Key informant, Lakes State)

At the wider community level, changes in the migratory patterns and preferences of flood-affected populations also set a new benchmark for extreme flooding events, superseding experiences of extreme events in past generational collective memory, including the severe flooding in the 1960s. Changes in migratory patterns, routes, and preferences compared to the past are attributed to the higher extreme hydrological regime. Below is one respondent's account:

> The whole land is left barren, and no one is eager to return to it. When we left the flooded areas, we were devastated. It flooded in 1917 (Red flood- reddish water), and in 1963 (Pawer-great dispersion flood), and those flooding events were tremendous, resulting in great dispersion of the population from the Twic East County. The recent flood (2019-2022) has created even greater dispersion: Twic population is no longer in Twic land. You will find Twic people in all places. (A chief from Twic County, Jonglei State)

Using NVivo coding references based on the thematic analysis of survey results, we find that 20% of referenced migration is taking place following past migration patterns, whereas 80% is a result of new migration patterns. Interstate migration and transboundary migration patterns (across national boundaries) each account for 17% of all references made about extreme flood-induced migration. Respondents frequently indicated that new migration routes are longer in distance and in duration than those taken in response to past flooding, and these changes have significantly impacted the most vulnerable part of the population, namely people with disabilities as well as women, children, and the elderly. These groups are disproportionally affected by the impacts of extreme flooding and must often relocate repeatedly in search for better services, such as in refugee camps in Ethiopia, Kenya and Uganda.

Migration patterns and preferences across different communities

The higher shift in the flood regime, coupled with the resulting environmental risks, has limited the availability of habitable space, resulting in migration. While the majority of populations across the Sudd region experienced flood-induced migration between 2019 and 2022, results also indicate that migration responses are highly heterogeneous, characterized by the emergence of new mobility patterns and increasing long-distance and transboundary movements. These shifts suggest a broader transformation of migration systems beyond incremental adaptation to flooding, reflecting deeper changes in social, livelihood, and environmental dynamics.

We asked participants about their communities' responses to flooding, which included (1) changes in transhumance, (2) previous migration patterns, (3) emergent patterns and preferences, (4) transboundary migration, and (5) interstate migration. These responses are not mutually exclusive as some displaced persons experienced cross-scale linkages between interstate migration and either previous or new emergent patterns. For instance, migration among the IDPs from Duk County in Jonglei State is a key response mechanism to extreme flooding. There, interstate migration accounts for 23% of the responses, previous migration patterns make up 25% of responses, and new emergent patterns and preferences account for 33% of migration patterns. The Duk distribution of migration patterns is approximately similar to those in Bor and Twic East counties, which are also from Jonglei State. Among the Bentiu elders in Unity State, changes in previous migration patterns and preferences account for 45% of the 'migration' theme analysis, interstate migration accounts for 10%, and transboundary migration accounts for 6%. It is important to note that migration is not a feasible or desirable adaptation strategy for all households. This finding is reflected in the limited long-distance migration observed among elderly populations in Unity State.

Jonglei State has the highest rate of migration across state lines, with large populations in the UN IDPs camps in Upper Nile and Central Equatoria states. These counties experience an upward trend in migration out of state. For instance, 75% (over 100,000 people) of the population from Twic East County during the 2019–2022 extreme flood migrated to states within South Sudan, Ethiopia, Kenya, Uganda, or DRC.

Participants from the counties in Unity State and Jonglei State shared several stories of their own and those of their relatives having experienced secondary migration to other IDP camps, or across international borders to refugee camps as they looked for better services and opportunities. For example, some South Sudanese populations that migrated to refugee camps in Ethiopia, Kenya, and Uganda were reportedly resettled to third countries, such as Australia, the U.S, Canada, and western Europe.

Dynamics of flooding, migration, conflict, and social systems

The interconnectedness of flooding, conflict, migration, and social systems in the Sudd region is highly complex as these

different processes are interlinked in rapidly changing environments. Respondents from all 16 community-level FGDs, across 10 counties, referred to flood-induced migration as both causing conflict and exacerbating tensions of conflict that are deeply rooted in past political or ethnic feuds. Patterns of conflict, however, are spread unevenly across impacted geographies. In some areas, such as Bor County, Twic East County, Duk County, and Fangak County in Jonglei State, and Panyikang County in Upper Nile State, widespread ethnic conflict preceded the 2019–2022 flood-induced migration. In these locations, conflict has been a much more significant driver of migration over the last four decades that were marked by a series of unrest including the 1983–2005 Sudanese civil war and the 2013–2018 South Sudanese internal war.

In the states of Jonglei, Unity, and Warrap, flood-induced migration and conflict interact in complicated ways, affecting different livelihood groups to different degrees. Unity and Jonglei States showed a higher prevalence of conflict and flooding, as these areas are where internal displacement, cross-state migration, and transboundary migration have occurred most frequently in the Sudd region. Results indicate new tensions and violent incidents arose between the host communities who are farmers and migrant pastoralists from Jonglei State, as well as among other various cattle-keeping groups over limited usable land. Below is a quote from a participant that puts our analysis into perspective:

> The flooding occurred everywhere, competition for scarce resources like dryland, grazing land, fishing islands exacerbated existing tensions between different communities and strained already weak local governance structures, ultimately creating fertile ground for violence between groups. (Key informant, Bor County, Jonglei State)

However, flooding was also perceived to reduce cattle-raiding activities by creating buffer zones between communities traditionally engaged in cattle-related conflicts. Among flood-induced IDPs, shared experiences of displacement have fostered a new form of unity, bringing previously antagonistic communities together in shared spaces where they are learning to coexist as neighbors.

Communities across the Sudd perceived flood-induced migration as a transformative force reshaping social systems, cultural practices, and collective identity. The displacement of populations into new environments was reported to expose migrants to different norms, lifestyles, and social structures, creating concerns about the erosion of long-established cultural identities and community systems. At the same time, these changes revealed intergenerational tensions, with older generations expressing concerns over the loss of traditions while younger generations viewed emerging adaptations and new social experiences more positively. Thus, flood-induced mobility was experienced as both a threat to cultural continuity and a pathway through which new forms of social identity and adaptation are evolving. Respondents across all 16 community groups emphasize how displacement forces them—due to interactions with other dominant cultures—to abandon their identities, their habits, their cultural understandings, and emotional attachments (Gieryn 2000) to their land and history. Three quotes from respondents illustrate this change in cultural identity:

> Typically, a family or clan stays in one place, and then they develop certain types of lifestyles, and certain cultural bonds. And over time, these clans/families have established community identities, their togetherness is very strong. However, when extreme floods appear, people move away from their places. The first challenge we usually face is that we do not move to one place; we are scattered. Some of us migrate to one place, and some move to other different places. So, our bond, because of the distance, starts to loosen. (A key informant, Panyikang County, Upper Nile State)
>
> We cherished our culture of dignity and respect. The family had a strong bond with respect between husbands and wives and their children. The moment we migrated to Mongalla, our cultural values began to shift. The families started faltering. Our relationship as a communal society was disappearing. A clan or family group used to face adversities or responsibilities collectively. This bond is breaking down. Populations are dissolving to adversary peer groups. (An elderly man, Duk County, Jonglei State)
>
> All the Twic people in all their respective new settlements are gaining new orientations and different characteristics. The impacts of floods on social values are far greater; we are wanderers who are subject to foreign orientation that is redefining our nature and character as a people. (A displaced Chief of Twic East County, Jonglei State)

It is evident from the survey results that the impacts of a higher flood regime transcend migration, with longer spatio–temporal migration resulting in transformative social changes among the migrants. Moreover, the impacts of extreme flooding can lead to conflict, which can further drive migration, which in turn may exacerbate conflict. These interwoven processes are qualitatively assessed and understood in the Sudd wetland for the first time.

Field observation and data analysis suggest that the impacts of flooding are becoming more detrimental in the Sudd region because of several intersecting dynamics:

1. The population in the Sudd region has been experiencing greater flood risks for the last half a decade, likely pointing towards the effects of climate change.

2. In the shadow of wars since the 1980 s, environmentally significant geomorphological changes have been occurring in the Sudd region without attention; reduction in channel capacity and floodplain storage, and the alteration of flow paths are shifting vulnerabilities across human and non-human actors across physical, economic, environmental, social, and cultural dimensions.
3. Community settlements within the Sudd region may have encroached on high-risk flood areas during the five decades of wars, as violence and multifaceted insecurity forced them to do so.
4. Village settlements that were historically located near the Sudd permanent wetlands and major river channels centuries ago, to benefit from access to fresh water and fertile land, have been transforming into more fixed urban centers.
5. Unplanned urbanization, in terms of oil production-related infrastructure development, rural flight, and population growth is happening rapidly with limited strategic decision-making processes in place.

Discussion and recommendations

This study investigates the changing dynamics of human responses to flooding and how these changes influence human wellbeing in the Sudd region. The findings demonstrate that flooding in the Sudd cannot be understood only as a hydrological hazard, but rather as a socio-hydrological process where environmental changes interact with livelihoods, mobility, conflict dynamics, and social institutions. Thus, the same system produces both resilience and vulnerability, depending on its intensity and timing. The discussion is organized across three interconnected levels. It first examines community-level adaptation to changing flood risk, before considering how these local responses collectively reshape migration, resource use, and human–environment interactions across the wider Sudd region. It then explores the longer-term societal transformations that emerge through changing demographic patterns, cultural relationships, and adaptation pathways (Mohamed et al. 2006; Rebelo et al. 2012; Caretta et al. 2023).

The extreme floods experienced between 2019 and 2022 represent a major disruption to human–wetland relationships in the Sudd. These floods have altered the availability of habitable land, transformed livelihood strategies, and challenged long-established forms of adaptation. While mobility has historically been an important adaptation strategy in the Sudd, the increasing persistence and unpredictability of flooding are reshaping migration patterns, with some movements serving as temporary coping responses and others contributing to longer-term societal change.

Community-level adaptation to changing flood risk

Livelihood disruption

The recent extreme flooding events demonstrate the immediate impacts of hydrological changes on household livelihoods in the Sudd. The 2019–2022 floods, described by Borgomeo et al. (2023) and Kose (2024) as among the most severe flood events recorded in the region, affected approximately one million people and displaced more than 300,000 people. This reflects broader concerns that increasing climate variability is altering long-established relationships between communities and hydrological systems, particularly in wetlands where livelihoods are closely tied to seasonal water dynamics (Mohamed and Savenije 2014; Rebelo et al. 2012). For communities whose livelihoods depend directly on land, water, livestock, and seasonal ecological cycles, prolonged inundation creates severe disruptions to everyday life. Such dependence illustrates the close relationship between environmental variability and livelihood vulnerability in flood-prone regions, where exposure and adaptive capacity shape differentiated outcomes (Rentschler et al. 2022).

It is important to highlight that flooding in the Sudd wetland has sustained livelihoods for generations. While the Sudd ecosystem and dependent populations rely on the seasonal flood cycle, extreme flooding—such as the floods from 2019 to 2022—can cause harm and push populations beyond their coping and adaptive capacities. Agricultural activities have become more constrained as cultivated areas become submerged, grazing areas become inaccessible, and livestock face increased exposure to disease and mortality. Consequently, households experience heightened food insecurity, increased vulnerability to disease, and reduced access to essential services. On the other hand, the same floodwaters that undermine land-based livelihoods create productive aquatic environments, increasing access to resources such as fish and water lilies. Fishing opportunities may increase in some areas, but our findings suggest that these benefits are unevenly distributed and cannot compensate for the wider loss of livelihood security.

The results show that communities with limited coping capacities face difficult choices when floodwaters persist: remain in increasingly hazardous environments or migrate in search of safety and livelihood opportunities. Thus, migration emerges not simply as a response to environmental pressure but as a survival strategy shaped by declining livelihood options. This finding contributes to emerging scholarship that increasingly views migration as a potential adaptation response to hydro-climatic change rather than solely as environmental displacement (Caretta et al. 2023; Falco et al. 2019; Chung et al. 2022a).

Survival migration and changing mobility decisions

Migration represents one of the most visible responses to increasing flood risk in the Sudd. However, the findings suggest that migration is not a single process or outcome. Rather, it exists along a continuum ranging from temporary relocation and seasonal movement to permanent displacement. In areas where floodwaters have remained for several years without receding, return becomes increasingly uncertain, encouraging households to seek safer locations within South Sudan or across international borders.

The increasing unpredictability of flood conditions has also changed perceptions of risk. When households cannot anticipate when waters will recede, investments in homes, livestock, infrastructure, and agricultural activities become increasingly risky. As a result, even during flood recession periods, communities may be reluctant to rebuild or invest in flood-prone areas. The limited availability of infrastructure—including roads, healthcare facilities, schools, housing, utilities, and communication networks—further reinforces migration pressures.

The findings reveal that some households remain in flood-affected areas due to limited resources, social obligations, or attachment to ancestral lands. Elderly populations and households without the financial or social capacity to undertake long-distance movement often experience constrained mobility or involuntary immobility. Therefore, human responses to flooding involve both mobility and immobility, depending on access to resources, social networks, and livelihood strategies. This supports growing recognition that climate mobility outcomes are heterogeneous and shaped by social, economic, and institutional conditions rather than environmental exposure alone (Nabong et al. 2023).

Changes in transhumance systems

Flooding has also transformed pastoral mobility patterns, particularly among communities dependent on cattle herding. Traditionally, transhumance in the Sudd has been a highly adaptive system that responds to seasonal variations in water, pasture, and grazing availability. However, the changing flood regime has disrupted these established patterns. Similar patterns have been observed in pastoral systems where mobility functions as an important strategy for managing climatic variability and resource uncertainty (Tekola, n.d.; Piemontese et al. 2024).

The sudden shift from predictable seasonal movements to more uncertain flood conditions has altered spatial and temporal grazing strategies. Several cases of cattle mortality were linked to difficulties associated with changing grazing routes, reduced access to suitable dry-season areas, disease exposure, and inadequate access to clean water and pasture. Pastoralists increasingly move cattle over longer distances in search of suitable environments, including higher dry ground outside traditional movement corridors.

These changes demonstrate that flooding affects not only where people live but also the broader ecological systems that support pastoral livelihoods. The disruption of transhumance represents a major transformation of human–environment interactions in the Sudd.

Indigenous knowledge, flood memory, and adaptation

Flood adaptation in the Sudd has historically depended on extensive indigenous ecological knowledge developed through generations of interaction with the wetland. The importance of such knowledge is increasingly recognized in climate adaptation research, particularly where formal environmental monitoring systems remain limited (Johnson 2019). Communities have accumulated knowledge about seasonal flood cycles, livestock movements, fishing practices, settlement locations, and resource availability. This knowledge is transmitted through oral histories, cultural practices, songs, place names, and everyday livelihood activities.

The findings reveal that intergenerational flood memory can function as an important adaptive resource. Communities that maintain continuity of residence are more likely to retain knowledge of environmental variability and appropriate responses to changing conditions. However, prolonged displacement can disrupt these knowledge transmission systems. Populations returning after long periods away from the Sudd may experience a knowledge gap, having lost direct connections with local hydrological rhythms and traditional adaptation practices.

Therefore, displacement creates a paradox: migration may protect households from immediate flood exposure, while prolonged separation from place may weaken the cultural and ecological knowledge systems that historically supported resilience. This highlights a broader challenge in adaptation planning, where responses that reduce immediate vulnerability may simultaneously transform social and cultural capacities over longer timescales (Haasnoot et al. 2013).

Heterogeneity in migration patterns and preferences across communities

Communities experiencing similar flood conditions may adopt different strategies depending on their ecological location and livelihood dependence. Populations from Fangak, Duk, Bor, and Twic counties in Jonglei State, as well as Rubkona County in Unity State, demonstrated stronger patterns of migration. These areas have experienced severe flooding combined with other pressures, including conflict-related insecurity, displacement histories, and limited access

to services. For many households in these locations, migration represents a necessary strategy to escape increasingly uninhabitable environments.

However, other communities showed different adaptation pathways. Among respondents from Akop Payam in Tonj North County and Wunrok in Twic County in Warrap State, Manga Port in Guit County in Unity State, and Panyikang County in Upper Nile State, migration was less frequently discussed as a dominant response. Instead, communities emphasized internal displacement within their respective states and continued reliance on wetland-based livelihoods, including fishing and the use of aquatic resources such as water lilies.

These differences illustrate that movement away from flood-affected areas is not always the preferred or feasible option. For some households, particularly elderly populations and those with limited financial resources, longer-distance migration may not be possible. The lower references to interstate migration (10%) and transboundary migration (6%) among elderly populations in Unity State, for example, demonstrate that mobility is strongly shaped by social and economic constraints. In such cases, people may remain close to their ancestral lands and maintain modified forms of previous livelihoods despite changing environmental conditions.

The experience of the Shilluk community in Panyikang County further demonstrates the importance of livelihood flexibility and cultural adaptation. Rather than relying primarily on migration, many Shilluk communities respond to flooding through mobility across river landscapes, temporarily leaving islands and moving toward areas on the western side of the Nile where some already have established connections. Their long history of fishing as a livelihood provides an important adaptive advantage. When cattle movements become impossible or livestock losses occur, and agricultural production is constrained by flooding, fishing provides an alternative source of food security. The existence of fishing institutions, skills, and knowledge transferred across generations strengthens their ability to adapt.

These examples demonstrate that migration should not be interpreted simply as either successful adaptation or failure. Movement can reduce immediate exposure and provide access to services, while remaining in place can also represent adaptation when communities possess appropriate livelihood strategies and ecological knowledge. Adaptation outcomes depend on the relationship between environmental change and existing social capacities.

Importantly, the extreme floods of 2019–2022 also generated new forms of environmental awareness and preparedness among communities. For several decades, many populations from the Sudd region had experienced displacement due to conflict, living as IDPs or refugees in other regions and countries. During those periods, many had limited experience with climate-related disasters of the scale observed during recent floods. The severity of these events created a renewed recognition of the growing impacts of climate change and the need for locally appropriate adaptation strategies. The flood experience has therefore contributed to the process of social learning. Communities have developed stronger awareness of environmental risks, the limitations of existing adaptation strategies, and the importance of preparing for future climate shocks. This suggests that extreme events can generate both vulnerability and new understanding on how communities interpret and respond to environmental change.

While these findings highlight how households and communities adapt to changing flood conditions, the cumulative effects of these local responses extend beyond individual communities to reshape migration patterns, resource use, and human–environment interactions across the wider Sudd region.

State and Sudd regional transformations

Changing flood regimes and shrinking habitable landscapes

At the landscape scale, the increasing persistence and unpredictability of flooding are reshaping the spatial organization of human activities in the Sudd. Unlike historical seasonal flooding, where communities adapted through predictable cycles of movement and resource use, recent flood events have created prolonged inundation that limits the availability of habitable land. Historical analyses of flooding in the Upper Nile region similarly demonstrate that communities developed adaptation strategies around recurring flood rhythms, which may become less effective under changing hydrological conditions (Johnson 1992, Johnson 2019).

The expansion and persistence of floodwaters reduce access to settlements, grazing areas, agricultural land, and essential services. This creates a situation where environmental change directly influences demographic patterns, as populations are forced to reconsider where and how they live. The Sudd is therefore experiencing a transition from adaptation to seasonal variability toward adaptation to prolonged hydrological uncertainty.

The reduction of habitable space also intensifies competition over remaining resources. Areas of higher ground become increasingly valuable for settlement, grazing, and cultivation, increasing pressure on landscapes that were previously shared through seasonal arrangements.

Shifting migration routes and mobility landscapes

The changing flood regime has produced increasingly complex migration pathways. Rather than following a single

direction, movements from flood-affected communities occur across multiple scales, including movement within counties, between states, and across national borders. These patterns reflect the interaction between flood exposure, livelihood opportunities, security conditions, and access to services.

Communities from areas such as Fangak, Duk, Bor, and Twic counties in Jonglei State, as well as Rubkona County in Unity State, demonstrate stronger migration pressures due to severe flood exposure combined with broader conflict-related vulnerabilities.

This aligns with climate mobility research emphasizing that migration decisions emerge from interacting environmental, economic, political, and social drivers (Caretta et al. 2023; Nabong et al. 2023). Movement toward towns, higher ground, IDP settlements, or neighboring countries reflects attempts to secure livelihoods, access services, and reduce exposure to environmental risks.

Competition over land, resources, and conflict dynamics

Flooding does not operate as an isolated driver of mobility, nor does it replace existing structural and political drivers of conflict in South Sudan. Rather, it interacts with and often amplifies pre-existing vulnerabilities, including armed violence, fragmented governance, and historical inter-community tensions. As floodwaters reduce available land, grazing areas, fishing grounds, and settlement space, competition over these resources can intensify, particularly in contexts where access rights are already contested or weakly governed.

This dynamic is further shaped by the widespread proliferation of small arms and light weapons across South Sudan. The availability of firearms at community level has lowered the threshold for violence in resource disputes and has increased the capacity of local actors to defend territory, cattle, and livelihoods. In flood-affected areas, where displacement brings previously separated groups into closer and often contested proximity, the presence of small arms can escalate what might otherwise be manageable disputes into violent confrontations. In this sense, flooding acts less as a direct cause of conflict and more as a spatial and material stressor that increases the likelihood of violence in already armed and fragile settings.

These dynamics are also embedded within a broader landscape of political fragmentation and the presence of multiple armed and political factions. In South Sudan, authority is often dispersed across state institutions, customary authorities, and armed actors aligned with different political or ethnic constituencies. This fragmentation affects how displaced populations are received, protected, or contested in new locations. In some cases, access to land, water, or settlement areas is mediated through politically aligned structures, which can reinforce exclusion or differential treatment of displaced groups. Consequently, mobility induced by flooding frequently intersects with existing political and military geographies, shaping both the direction and safety of movement.

Inter-ethnic relations further mediate these processes. Historical patterns of cattle raiding, revenge violence, and territorial competition have produced long-standing tensions among different groups in the Sudd region and beyond. Flood-induced displacement often brings these groups into closer spatial proximity, particularly in urban centers, dike-protected settlements, and higher ground areas. While this can intensify latent tensions over resources, several respondents also described cases where shared experiences of flood displacement created new forms of coexistence and temporary social cohesion among groups previously considered adversaries. In some contexts, flooding has also altered the geography of cattle raiding by creating seasonal barriers or "buffer zones," which temporarily reduce the feasibility of inter-community raids.

Overall, these findings support a compound-risk perspective in which flooding interacts with violence, mobility, and governance in non-linear and context-specific ways. These interactions should not be interpreted as simple causal pathways from climate hazard to conflict. Instead, flooding, migration, armed violence, and social reconfiguration operate as co-evolving processes within a complex socio-hydrological system, where outcomes depend on the configuration of local power relations, resource governance, and security conditions (Borgomeo et al. 2023).

In terms of the hierarchy of drivers of mobility, the findings suggest that flooding is a primary proximate driver of displacement during the 2019–2022 period in the study areas, particularly in the Sudd floodplain where inundation directly rendered settlements uninhabitable. However, flooding rarely operates in isolation. It acts as a triggering and amplifying factor that intersects with deeper structural drivers, including chronic insecurity, livelihood fragility, weak infrastructure, and the presence of armed actors. Conflict and insecurity therefore remain underlying drivers of mobility in the broader South Sudanese context, while flooding is best understood as a dominant environmental trigger that accelerates and reshapes existing patterns of displacement rather than replacing them. These regional transformations demonstrate that the consequences of extreme flooding extend beyond changes in landscapes and mobility, contributing to broader societal changes that influence cultural continuity, demographic redistribution, and the long-term evolution of adaptation pathways.

Long-term societal transformation and adaptation pathways

The preceding discussion demonstrates that responses to flooding in the Sudd unfold across multiple spatial and

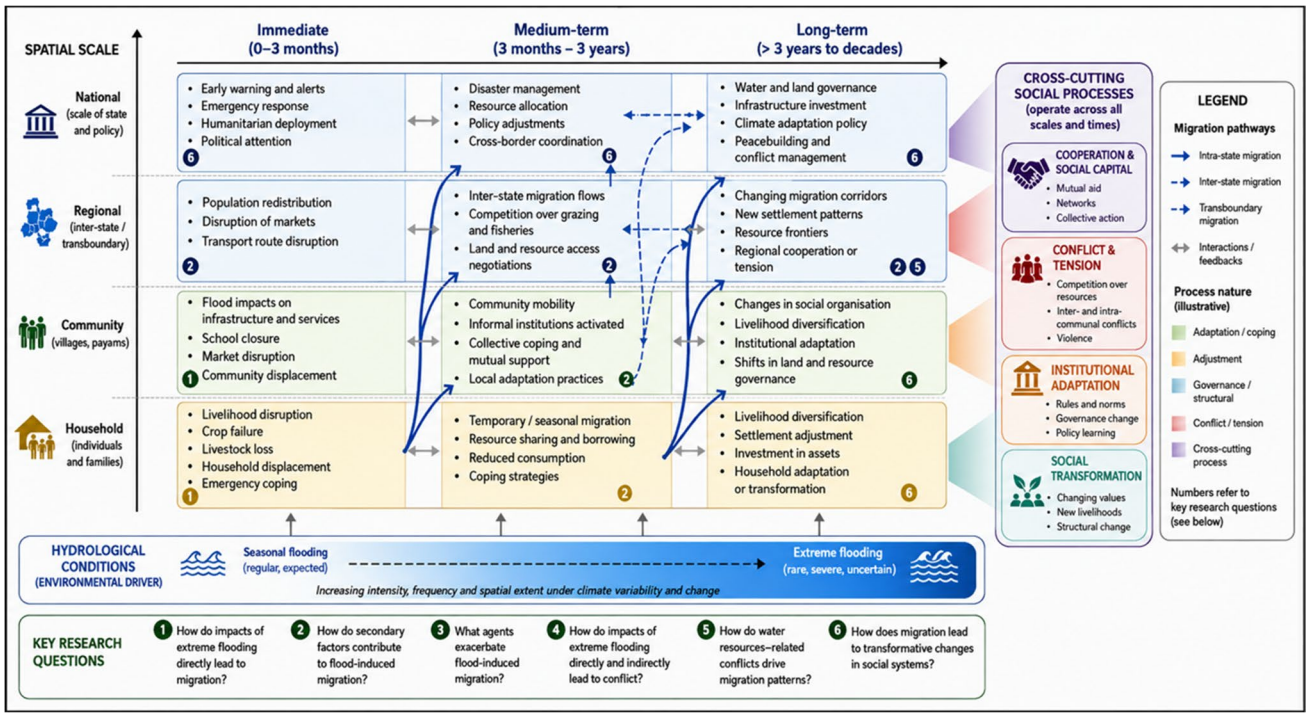


Fig. 9 Spatial and temporal dynamics of flood-induced adaptation, migration, and social change in the Sudd

temporal scales rather than through a simple sequence of cause-and-effect relationships. Figure 9 synthesizes these findings into a spatio-temporal socio-hydrological framework that illustrates how hydrological change interacts with household decision-making, community adaptation, regional migration, and longer-term institutional and societal change. Rather than presenting conflict or social transformation as predetermined outcomes of migration, the framework conceptualizes them as dynamic processes that emerge through interactions among environmental conditions, mobility, governance, and social institutions operating across different scales and time horizons.

The framework recognizes flooding as the underlying environmental driver that varies from predictable seasonal inundation to increasingly frequent and severe extreme flood events. At the household scale, flooding immediately disrupts livelihoods through crop losses, livestock mortality, displacement, and reduced access to essential resources, prompting a range of coping responses that include temporary migration, resource sharing, and livelihood adjustment. At the community scale, these household responses collectively influence patterns of mobility, social support, and local adaptation. Over longer periods, migration reshapes regional settlement systems, resource access, and demographic distribution, while national institutions increasingly influence adaptation through governance, disaster management, infrastructure investment, and climate policy.

Migration therefore represents neither a purely adaptive nor maladaptive response but a dynamic process whose outcomes vary across space and time. Short-term mobility can reduce exposure to flood hazards and diversify livelihood opportunities, whereas prolonged displacement may alter settlement patterns, increase pressure on receiving areas, and reshape social relationships. Likewise, competition over land, fisheries, grazing resources, and humanitarian assistance may generate tensions under some conditions, while strengthened cooperation, social networks, and institutional learning may emerge under others. The framework therefore emphasizes feedback between environmental change, mobility, governance, and social organization rather than fixed causal pathways.

The principal contribution of this conceptual framework does not lie in introducing entirely new components, as flooding, migration, conflict, and institutional adaptation have each been widely studied independently. Instead, its novelty lies in integrating these interacting processes within a single socio-hydrological framework that is empirically grounded in extensive fieldwork conducted across one of the world's largest and least-studied wetland systems. By explicitly linking spatial scales with temporal dynamics, the framework provides a structured interpretation of how local adaptation decisions accumulate to influence broader regional and national processes, while institutional responses subsequently shape future vulnerability and adaptation opportunities.

Cultural transformation and changing relationships with place

Long-term displacement can progressively reshape relationships between communities and their ancestral landscapes. Within the Sudd, land represents not only a productive resource but also the foundation of identity, customary governance, and cultural continuity. Extended displacement may weaken these place-based relationships, particularly when younger generations grow up outside traditional environments with fewer opportunities to maintain customary practices and ecological knowledge.

However, the findings also demonstrate that social transformation is not solely characterized by cultural loss. Communities actively reconstruct social institutions, adapt livelihood strategies, and establish new forms of cooperation in response to changing environmental conditions. These adaptive processes illustrate that social transformation is an ongoing negotiation between continuity and change rather than a linear consequence of displacement.

Demographic redistribution and evolving settlement systems

The continuation of increasingly severe flooding is likely to reshape settlement geography throughout the Sudd. Areas experiencing prolonged inundation may support fewer permanent settlements, while higher-elevation locations, urban centers, and areas with improved infrastructure are likely to receive growing populations. Such demographic redistribution has important implications for land-use planning, infrastructure development, service provision, and environmental management.

Migration over longer distances may also alter traditional social structures by weakening kinship-based support networks and customary institutions that have historically depended on close geographical proximity. Consequently, adaptation planning must consider not only reducing physical exposure to flood hazards but also maintaining the social and institutional systems that underpin long-term resilience.

Institutional adaptation and cross-scale resilience

Repeated flooding and migration continuously reshape the institutions that support adaptation within the Sudd. Customary governance systems, collective resource management, and local conflict-resolution mechanisms are closely connected to place-based social relationships and may become increasingly difficult to sustain under prolonged displacement. At the same time, new governance arrangements, partnerships, and institutional learning can emerge as communities, humanitarian organizations, and government agencies respond to evolving environmental challenges.

The findings therefore demonstrate that adaptation outcomes differ across spatial and temporal scales. Strategies that reduce immediate household vulnerability may generate longer-term pressures elsewhere, while regional or national interventions may strengthen resilience through improved governance, infrastructure investment, and disaster preparedness. Understanding these cross-scale interactions is fundamental for developing adaptation strategies that integrate hydrological processes with community knowledge, migration dynamics, institutional change, and long-term social resilience across the Sudd socio-hydrological system.

Research limitations

This study addresses an important but underexplored dimension of climate adaptation in a region where primary data collection remains extremely challenging. Conducting fieldwork-based research on migration and flood adaptation in the Sudd is difficult because of limited infrastructure, poor accessibility, insecurity, and the physical complexity of the wetland environment. These factors restrict the ability to conduct extensive longitudinal observations across the entire region.

The study does not capture the full geographic, ethnic, and livelihood diversity of the Sudd. Although the research included communities with different experiences of flooding and adaptation, the findings should be interpreted within the contexts represented by the sampled locations. Other communities may experience different migration pathways and adaptation strategies.

Furthermore, migration decisions are influenced by multiple household-level factors, including economic conditions, social networks, security considerations, and personal preferences. While this study identifies broad patterns of adaptation and mobility, it does not fully capture every determinant influencing individual migration decisions.

Recommendations

This section presents policy recommendations emerging from the study findings. The recommendations are structured across community, state, and national/Sudd regional scales to address the multi-level nature of flood risk and adaptation challenges in the Sudd. Given that flooding in the Sudd is not only a hydrological hazard but also a driver of livelihood disruption, migration, conflict, and social transformation, effective responses require integrated approaches that combine disaster risk reduction, livelihood support, social protection, and long-term governance. Such integrated approaches are increasingly emphasized in climate adaptation research, particularly where risks emerge from

interacting environmental and social processes (Haasnoot et al. 2013; Caretta et al. 2023).

Community-level recommendations

Because flood-induced displacement affects not only physical assets and livelihoods but also social networks, cultural practices, and community institutions, interventions at the community level should strengthen both material and social dimensions of resilience. This requires moving beyond reactive emergency responses toward locally driven systems that enable communities to anticipate, absorb, and adapt to changing flood conditions.

Community-based flood monitoring systems and early warning mechanisms should be strengthened through locally accessible communication channels, including community flood observers, traditional knowledge networks, radio communication, and other locally appropriate technologies. Combining local knowledge with scientific monitoring has been identified as an important pathway for improving climate-risk preparedness and locally appropriate adaptation (Alfieri et al. 2018; Mayen et al. 2023). These systems should incorporate indigenous knowledge of flood patterns, seasonal changes, livestock movements, and environmental indicators, recognizing that local knowledge remains an important foundation for disaster preparedness.

State-level recommendations

At the state level, increasing flood-induced mobility requires planning systems that recognize displacement as a long-term process rather than a temporary humanitarian event. This reflects broader climate mobility scholarship that recognizes displacement and migration as dynamic processes requiring long-term governance responses (Chung et al. 2022a; Caretta et al. 2023). As displaced populations interact with host communities, state authorities should prioritize conflict-sensitive settlement planning, negotiated land-use arrangements, and service delivery approaches that respond to changing population movements.

The proximity of many IDP settlements in Unity State, Upper Nile State, Central Equatoria, Jonglei State, and Warrap State to government and humanitarian institutions provides an opportunity to strengthen social cohesion among displaced populations from different ethnic communities. State authorities should establish platforms that bring together local governments, traditional leaders, host communities, and IDP representatives to facilitate dialogue, coordinate adaptation strategies, and address emerging tensions.

State-level planning should strengthen conflict-sensitive, locally led resource governance that enables displaced and host communities to jointly manage flood adaptation. Rather than establishing new governance structures, implementation should build on existing customary institutions and local conflict-resolution mechanisms by supporting inclusive planning forums involving local authorities, traditional leaders, women, youth, pastoralists, farmers, fishers, and displaced communities. Participatory resource mapping, seasonal mobility agreements, negotiated access to grazing land, fisheries and water points, and equitable investment in shared infrastructure can help reduce resource competition while strengthening collective resilience to increasingly variable flood conditions.

States should develop proactive displacement planning that anticipates, rather than simply responds to, the long-term consequences of recurrent flooding. This should include identifying areas at risk of future displacement, planning suitable locations for temporary and permanent settlement, establishing transparent arrangements for land access and tenure, and strengthening locally led mechanisms for mediation between displaced and host communities. Integrating displacement into state land-use planning, infrastructure investment, and climate adaptation strategies would help reduce uncertainty, improve service provision, and lower the risk of future conflict.

National/Sudd regional-level recommendations

At the national scale, flood governance in South Sudan requires a shift from treating floods primarily as humanitarian emergencies toward integrated socio-hydrological management. Such a shift is consistent with emerging approaches that move beyond hazard management toward understanding coupled human–water systems and adaptive governance (Mohamed and Savenije 2014; Haasnoot et al. 2013). The Government of South Sudan should strengthen long-term flood risk governance through improved hydrological monitoring, climate information systems, population exposure assessment, and coordinated displacement planning. These systems should support evidence-based decision-making and enable authorities to anticipate rather than respond only after disasters occur.

Protecting the Sudd is not only an environmental priority but also essential for sustaining the livelihoods, cultural systems, and well-being of the communities who depend on the wetland. This reflects the broader recognition that wetlands provide interconnected hydrological, ecological, and social functions that must be considered together in sustainable development planning (Rebelo et al. 2012; Sutcliffe and Brown 2018).

Conclusion

We conducted an empirical study in the environments of flood-affected populations in the Sudd region of South Sudan to investigate how people respond to the impacts of

extreme flooding. Using a multi-method approach, including focus group discussions and semi-structured interviews, qualitative mobility mapping, and field observations, our analyses reveal that flooding in the Sudd region has become more severe, with high agreement among community members of greater flood risk. Whilst seasonal flooding is needed for livelihoods of the communities and the vitality of the Sudd wetlands ecosystems, excessive flooding (such as that experienced in 2019–2022) disrupts a delicate balance of life within the Sudd habitats. Direct impacts of this high-magnitude flood regime, coupled with the resulting environmental risk have significantly limited the availability of habitable space and resources, resulting in migration as a last resort survival strategy. This forced migration is distinguished from seasonal adaptation practices, which act as livelihood strategies used by agro-pastoral communities in the Sudd region to navigate the seasonal impacts of climate variability, following water movements and vegetation growth cycles. The increased severity of recent flood events has led to longer migratory patterns and movements among both the pastoralists and the wider population. Results, however, indicate heterogeneity in migratory patterns across different communities in the Sudd region, including within-state displacement, interstate migration, and transboundary migration, which are dependent on the differing experiences of past flood impacts.

Our analysis of the field data advances a conceptual understanding that illustrates the complex interconnected dynamics of multiple variables, including how extreme flooding causes migration, and how migration in turn leads to conflict, which leads to further migration, and often results in social transformation through assimilation or clashes of cultural identities.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to the nature of the data and considerations related to participants confidentiality and research ethics, the data are not publicly available. Request for access should be directed to the corresponding author.

Contribution

This study provides the first systematic, empirical investigation of how extreme flooding is reshaping human adaptation dynamics in the Sudd wetlands of South Sudan. It makes three key contributions to understanding flood risk and adaptation within this complex socio-hydrological system. First, the study addresses a major empirical gap by presenting a field-based analysis of flood-induced migration dynamics in a region where in situ data on human mobility and adaptation remain highly limited. Second, beyond its empirical findings, this study develops a novel spatio-temporal socio-hydrological framework that integrates hydrological change, migration, governance, institutional adaptation, and social transformation within a single analytical model. By explicitly linking household, community, regional, and national processes across immediate, medium-term, and long-term timescales, the framework moves beyond linear representations of flood impacts to demonstrate how adaptation emerges through dynamic cross-scale interactions and feedback. The framework provides a transferable conceptual basis for analyzing human responses to flooding in the Sudd and other climate-vulnerable wetland systems. Third, the study contributes methodologically by integrating qualitative mobility mapping with systematic thematic analysis using thematic analysis to examine both the spatial patterns and social drivers underlying migration decisions. These approaches enable a deeper understanding of how communities interpret, negotiate, and adapt to changing flood conditions within a highly dynamic wetland landscape.

Future Research

Future research should build on these findings through long-term monitoring of flood dynamics, population movements, and social transformations in the Sudd. Integrating hydrological observations, remote sensing, demographic data, and community-based knowledge would provide a more comprehensive understanding of how the Sudd socio-hydrological system evolves under increasing climatic and socioeconomic uncertainties. Future studies should particularly focus on: (1) evaluating the resilience and long-term effectiveness of community-based adaptation strategies under different climate change scenarios; (2) developing dynamic models of population distribution and mobility patterns in relation to changing flood extents and future socioeconomic conditions; and (3) examining trends in conflicts over water and environmental resources to inform more effective approaches for managing resource-based communal conflicts in the Sudd.

Addressing these research priorities through interdisciplinary approaches will enhance understanding of the Sudd's socio-hydrological evolution by capturing the complex interactions between environmental change, human adaptation, mobility, and social transformation. Such knowledge will be critical for anticipating future trajectories and supporting sustainable adaptation pathways under continued climate and socioeconomic change.

Acknowledgements Authors express their appreciation to Samaritan's Purse, World Food Programme (WFP), and UNHCR for providing flights and accommodations during the field study; their support allowed full focus on research without the worry of travel logistics and finding housing. Authors would like to thank authorities in states of Upper Nile, Warrap, and Unity, as well as coordinators in charge

of Internal Displaced Persons (IDPs) camps in Mongalla, Malakal, and Bentiu for their help with mobilization of research participants. Authors would like to extend their gratitude to the research assistants for administrative support, and to the translators for translating discussions and transcripts from the Shilluk, the Nuer, and the Dinka languages to the English language.

Author contributions Kevin G. Wheeler: Supervision, Review and Editing. Amelie Paszkowski: Visualization, Reviewing and Editing. Steve-Kroll: Reviewing and Editing. Jim W. Hall: Funding acquisition, Supervision, Reviewing and Editing.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Adger W. Neil, Ricardo Safra de Campos, and Colette Mortreux (2018) "Mobility, Displacement and Migration, and Their Interactions with Vulnerability and Adaptation to Environmental Risks." Pp. 29–41 in *Routledge Handbook of Environmental Displacement and Migration,* edited by Robert McLeman and François Gemenne. Abingdon, UK: Routledge. https://doi.org/10.4324/9781315638843-3

Alfieri L, Cohen S, Galantowicz J, Schumann GJP, Trigg MA, et al. (2018) A global network for operational flood risk reduction. Environ Sci Policy 84:149–158. https://doi.org/10.1016/j.envsci.2018.03.014

Andu, Zakaria Lukwasa Tadesse Terefe, Zeleke Kassahun Ture, Beketie Desalegn Y., Ayal (2022) Spatio-temporal rainfall variability and its linkage with large scale climate oscillations over the Republic of South Sudan Climate Services 28100322. https://doi.org/10.1016/j.cliser.2022.100322

Blair P, Buytaert W (2016) Socio-hydrological modelling: a review asking "why what and how?" Hydrol Earth Syst Sci 20(1) 443-478. https://doi.org/10.5194/hess-20-443-2016

Borgomeo E, Chase C, Salazar Godoy N, Osei Kwadwo V (2023) Rising from the Depths: Water Security and Fragility in South Sudan. World Bank, Washington, D.C. https://doi.org/10.1596/978-1-4648-1943-8

Caretta MA, Fanghella V, Rittelmeyer P, Srinivasan J, Panday PK, et al. (2023) Migration as adaptation to freshwater and inland hydroclimatic changes? A meta-review of existing evidence. Clim Change 176(8):109. https://doi.org/10.1007/s10584-023-03583-3

Chol JW, Deng Majok, Hall KG, Wheeler M, Bernhofen CA, Di Vittorio KM, Strzepek (2026) Geospatial Analysis of Population Exposure to Flooding in the Sudd Region South Sudan ABSTRACT. J Flood Risk Manag 19(1). https://doi.org/10.1111/jfr3.v19.110.1111/jfr3.70168

Chung J-h, Buswala B, Keith M, Schwanen T (2022) Climate mobilities into cities: a systematic review of literature from 2011 to 2020. Urban Climate 45:101286. https://doi.org/10.1016/j.uclim.2022.101286

De Groeve T, Poljanšek K, Vernaccini L (2014) Index for Risk Management (InfoRM): Concept and Methodology, Version 2014. Publications Office of the European Union, Luxembourg. https://doi.org/10.2788/78658

Di Vittorio CA, Georgakakos AP (2021) Hydrologic modeling of the Sudd Wetland using satellite-based data. J Hydrol Reg Stud 37:100922. https://doi.org/10.1016/j.ejrh.2021.100922

Evans-Pritchard EE (1940) The Nuer: A Description of the Modes of Livelihood and Political Institutions of a Nilotic People. Oxford, UK: Clarendon Press.

Falco C, Galeotti M, Olper A (2019) Climate change and migration: is agriculture the main channel? Glob Environ Change 59:101995. https://doi.org/10.1016/j.gloenvcha.2019.101995

Feng MJ, Clark T, Karpouzoglou A, Dewulf W, Buytaert D, Hannah (2017) HESS Opinions: A conceptual framework for assessing socio-hydrological resilience under change Hydrology and Earth System Sciences 21(7) 3655-3670. https://doi.org/10.5194/hess-21-3655-2017

Gieryn TF (2000) A space for place in sociology. Annu Rev Sociol 26:463–496. https://doi.org/10.1146/annurev.soc.26.1.463

Haasnoot M, Kwakkel JH, Walker WE, ter Maat J (2013) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob Environ Change 23(2):485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Howell PP (1983) The impact of the Jonglei Canal in the Sudan. Geogr J 149(3):286–300. https://doi.org/10.2307/634003

Howell PP, Lock M, Cob S (eds.) (1988) The Jonglei Canal: Impact and Opportunity. Cambridge, UK: Cambridge University Press.

Johnson DH, Anderson DM (eds.) (1988) The Ecology of Survival: Case Studies from Northeast African History. London: Lester Crook Academic Publishing; Boulder, CO: Westview Press.

Johnson, Douglas H (1988) "Adaptation to Floods in the Jonglei Area of the Sudan: An Historical Analysis." Pp. 173–192 in *The Ecology of Survival: Case Studies from Northeast African History,* edited by Douglas H. Johnson and David M. Anderson. Boulder, CO: Westview Press https://doi.org/10.4324/9780429310249-9

Johnson DH (1992) Reconstructing a history of local floods in the Upper Nile region of the Sudan. Int J Afr Hist Stud 25(3):495–524

Johnson DH (2019) Adaptation to Floods in the Jonglei Area of the Sudan: An Historical Analysis. In: Johnson DH, Anderson DM (eds) The Ecology of Survival: Case Studies from Northeast African History. Routledge, London, UK, pp 173–192. https://doi.org/10.2307/219027

Kose M (2024) Threats of climate change and floods in South Sudan. Eurasian Journal of Agricultural Research 8(1):15–23

Kothari, Rishav (2024) "South Sudan Warns of Widespread Floods as Lake Victoria Hits 128-Year High." *The Watchers,* July 12, 2024

Kratli S (2015) Valuing Variability: New Perspectives on Climate Resilient Drylands Development. London: International Institute for Environment and Development. https://www.iied.org/10128iied.

Kroll-Smith S, Leon-Corwin M (2023) Blurring genres: an agenda for the study of climate change. Sociol Inq 93(2):216–224. https://doi.org/10.1111/soin.12524

Mayen JV, Wood E, and Frazier T (2023) "Practical Flood Risk Reduction Strategies in South Sudan." *Journal of Emergency Management* 20(8):123–136. https://doi.org/10.5055/jem.0669

McLeman RA, Hunter LM (2010) Migration in the context of vulnerability and adaptation to climate change: insights from analogues

Abstract WIREs Climate Change 1(3) 450-461. https://doi.org/10.1002/wcc.v1:310.1002/wcc.51

Mohamed YA, Savenije HHG (2014) Impact of climate variability on the hydrology of the Sudd wetland: signals derived from long-term (1900–2000) water balance computations. Wetl Ecol Manag 22(2):191–198. https://doi.org/10.1007/s11273-014-9337-7

Mohamed YA, Savenije HHG, Bastiaanssen WGM, and van den Hurk BJJM (2006) "New Lessons on the Sudd Hydrology Learned from Remote Sensing and Climate Modeling." H*ydrology and Earth System Sciences* 10(4):507–518. https://doi.org/10.5194/hess-10-507-2006

Nabong EC, Hocking L, Opdyke A, Walters JP (2023) Decision-making factor interactions influencing climate migration: a systems-based systematic review. Wires Clim Change 14(4):e835. https://doi.org/10.1002/wcc.835

Petersen G (2008) "The hydrology of the Sudd: hydrologic investigation and evaluation of water balances in the Sudd Swamps of Southern Sudan." PhD dissertation, Department of Hydrology, Christian-Albrechts-Universität zu Kiel.

Piemontese L et al (2024) Over-reliance on water infrastructure can hinder climate resilience in pastoral drylands. Nat Clim Chang 14(3):267–274. https://doi.org/10.1038/s41558-024-01929-z

Pouladi P, Abbas A, Amir M, Mohammad HA (2020) "Socio-Hydrological Framework for Investigating Farmers' Activities Affecting the Shrinkage of Urmia Lake; Hybrid Data Mining and Agent-Based Modelling." Hydrol Sci J 65(8):1249-1261. https://doi.org/10.1080/02626667.2020.1749763

Rebelo L-M, Senay GB, McCartney MP (2012) Flood pulsing in the Sudd Wetland. Earth Interact 16(1):1–19. https://doi.org/10.1175/2011EI382.1

Rentschler JE, Salhab M, Jafino BA (2022) Flood exposure and poverty in 188 countries. Nat Commun 13:3527. https://doi.org/10.1038/s41467-022-30727-4

Schwatke C, Dettmering D, Bosch W, Seitz F (2015) DAHITI—an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. Hydrol Earth Syst Sci 19:4345–4364. https://doi.org/10.5194/hess-19-4345-2015

Scoones I (1998) Sustainable rural livelihoods: a framework for analysis. IDS Working Paper 72. Brighton, UK: Institute of Development Studies.

Shweta J (2017) "Vulnerability and Climate Change Induced Human Displacement." Consilience 17: 103-142. https://doi.org/10.7916/consilience.v0i17.3915

Sutcliffe E, Brown J (2018) Water losses from the Sudd Hydrological Sciences Journal 63(4) 527-541. https://doi.org/10.1080/02626667.2018.1438612

Sutcliffe JV, Parks YP, Dugdale G (1989) The Sudan Floods of 1988. Hydrol Sci J 34(3):355–364. https://doi.org/10.1080/02626668909491339

Tatem AJ (2017) WorldPop, open data for spatial demography. Sci Data 4:170004. https://doi.org/10.1038/sdata.2017.4

Thiede B, Gray C, Mueller V (2016) Climate Variability and Inter-Provincial Migration in South America". *Global Environmental Change* 41:228–240.Trigg, Mark A., Jeffrey C. Neal, Christopher C. Sampson, Michael A. Smith, Andrew M. Bates, Paul D. Bates, and others. 2016. "The credibility challenge for global fluvial flood risk analysis. Environ Res Lett 11(9):094014. https://doi.org/10.1088/1748-9326/11/9/094014

United Nations Environment Programme (UNEP) (2018) South Sudan: *First State of Environment and Outlook Report 2018.* Nairobi, Kenya: United Nations Environment Programme.

Ward PJ, van der Wim J, de Moel H, Winsemius HC et al (2013) Assessing flood risk at the global scale: the role of global flood models. Environ Res Lett 8(4):044014. https://doi.org/10.1088/1748-9326/8/4/044014

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.