Human Exposure and Adaptation to Flood Risk in the Sudd



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For my father, Chief Majok Chol Jok

—Late Head Chief of the Nyarweng Dinka/Duk Payuel—

who never saw this adventure, but whose legacy inspired it.

"When we talk of flood control, we usually think of dams and deeper river channels, to impound the waters or hurry their run-off. Yet neither is the ultimate solution, simply because floods are caused by the flow of water downhill. If the hills are wooded, that flow is checked. If there is a swamp at the foot of the hills, the swamp sponges up most of the excess water, restores some of it to the underground water supply and feeds the remainder slowly into the streams. Strip the hills, drain the boglands, and you create flood conditions inevitably. Yet that is what we have been doing for years."

~ **Hal Borland**

Apportion of credit

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Author personal inspiration for the study

I was raised amidst the seasonal rhythms of the Sudd in Gak village, Duk Payuel, where my father was the Head Chief of the Nyarweng Dinka in South Sudan. It was here, while navigating floodwaters to herd cattle and fetching water, that I first understood the profound truth that 'water is life.' My upbringing—deeply rooted in the culture and knowledge of the Nilotic people—provided a front-row seat to the vulnerabilities and resilience of our environment. During my time growing up, I observed that the fortunes of our villages have always depended on seasonal flooding. Water is life, and we had plenty of it, regular rains, and free-flowing groundwater. The land was exceptionally fertile, and during the good years, every household's farm yielded unprecedented harvests. Warm weather kept the pastures green and lush, ensuring the cattle grew strong and healthy. As if this abundance weren't enough, the White Nile brimmed with fish, overflowing into seasonal streams and ponds—sometimes so shallow that fish could be caught by hand or simply stepped on. Yet this bounty came with a demand: in the wet seasons, I spent my days shepherding cattle with feet constantly soaked in floodwaters, and in the dry, I traversed the cracked clay Earth barefoot. I also had strange experiences as a child, facing head-on the influence of increasing industrialization and colonization. What I experienced with unannounced water project involved digging a canal through villages. At dawn, the villagers woke up to the deafening sound of the tractor digging the canal. This gigantic machine ran dawn to dusk. “It must be in a hurry,” the villagers would say to one another. As it muscled its way to Duk land, through the thick jungle, on wet clay and sand, reshaping the terrain. Industrial technology was still alien to us. We knew that powerful machines existed, but to see one and hear one and breathe its fumes was frightening. Eventually our village chiefs and elders pieced together what was happening. The then Egyptian government and Sudanese government were digging a canal, which would later be named the Jonglei Canal. The rivers provided life to our people. Generations had learned to live with their rising and falling cycles. However, in 1987, the Sudanese civil war turned my world upside down, robbing me of my childhood and my anticipated future societal duties. At just ten years old, I was ripped away from my family, our cattle, and the Sudd, embarking on a 14-year journey as a refugee. My education began at age 13 in the shade of a tree in Ethiopia, where I used the sand as a notebook and my feet as an eraser. Following high school in Kenya, the United States Refugee Program (USRP) resettled me from the Kakuma camp to Phoenix, Arizona, in 2001, marking the start of my new academic life. In hindsight, these experiences were not merely memories but an early education in the vital interplay between water, livelihood, and environmental stewardship, driving my aspiration to pursue this research. Pursuing this PhD thesis has offered a rare opportunity to reconnect with the Sudd and embark on a long-life research project I have always held close to my heart. Drawing on my lived experiences and the trials I endured growing up in the Sudd region, I was driven to conduct community-based research that directly engages with the marginalized, flood-affected populations in their natural setting.

Abstract

The Sudd wetland in South Sudan extends over 90,000 km2. Large-scale flood events in recent years (2019-2024) are said to have led to the displacement of an estimated 1.8 million people. However, these estimates are approximate and to date there has not been a systematic analysis of population exposure to flooding in the Sudd region. This study seeks to achieve this first aim by using global flood modelling, satellite observations of flood extent, and global gridded population datasets to analyze population exposure. Whilst adaptation to flooding has always been a feature of human interactions with the Sudd, the changing dynamics that are increasingly threatening human well-being have not been studied comprehensively. To fill this gap, a field study was conducted amongst flood-affected populations to investigate human adaptation and migration dynamics to flood risk. Using accounts of migration patterns derived from field visits, and population exposure scenarios from flood maps at a range of periods, this thesis examines the potential impact of future flooding regimes on regional migration flows. Overall, this thesis maps the geospatial distribution of flood hazards and population exposure in the Sudd region, investigates current human adaptation and migration dynamics in response to the 2019–2024 extreme flood events, and assesses the impact of future flooding regimes on migration flows in the Sudd region. The results of this modelling indicate that 0.8-2.9 million people are currently exposed to the 100-year return period flood extent. The field data reveal that unprecedented flooding in the years 2019-2024 had highly disruptive impacts for local communities and impeded deeply engrained seasonal migration routes. Furthermore, perceptions of an upward shift in the flood regime among the populations is high, leading to longer migration patterns and movements among both the pastoralists and the general populations, with a shift towards

upstream and upland regions. As dry land becomes scarce in states of Unity, Upper Nile and Jonglei, local displacement is becoming less viable. This shift is expected to significantly drive inter-state movement and transboundary migration into Ethiopia, Kenya, Uganda and the DRC. 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 interact to shape adaptation pathways in the Sudd and other climate-sensitive wetland systems. This thesis provides the first comprehensive assessment of flood exposure, human adaptation, and climate-induced migration in the Sudd region and introduces an integrated methodology combining global flood and population datasets with extensive field-based evidence to produce the first climate-informed migration scenarios for one of the world's most data-scarce and inaccessible floodplain systems.

List of Publications

This is an integrated thesis and is comprised of work that has been published in or submitted to the following peer-reviewed journals.

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Acronyms/Definitions

Terms/Acronyms	Definition
AA	Administrative Area- is a territorial unit established by the national government in South Sudan that is administered separately from the country's states. It has a status broadly equivalent to a state but is created for special political or administrative reasons.
Anuak	A Nilotic ethnic group whose residence lies along river banks on both sides of the border of South Sudan and Ethiopia.
Baap	A Nuer word, which means a sweeping force of nature that carries away everything- human, trees, livestock, settlements Etc., in reference to the magnitude of the 2019-2024 extreme flooding.
Bahr	Arabic word for sea/river.
Bahr el Ghazal	The river of the gazelles.
Bahr el Jebel	The river of the mountain.
County	An administrative division below the state level.
CPA	Comprehensive Peace Agreement, signed on January 9, 2005, between the Sudan Government and Sudanese People Liberation Army/Movement (SPLA/M). The CPA gave the people of Southern Sudan the right to exercise a referendum in 2011, giving birth to the independence of the Republic of South Sudan on July 9th that year.
Dinka	A Nilotic ethnic group known as the Jieng people in South Sudan.

FOA	Food and Agriculture Organization of the United Nations.
High land	Term used to describe higher, better drained land, where people have more permanent homesteads, and where they farm.
IDP Camps	Internal Displaced Persons (IDPs) camps.
Intermediate land	Land lying in level between high land and toic/swamps, usually associated with rain-flooded grasslands.
IOM	International Organization for Migration.
IPCC	Intergovernmental Panel on Climate Change.
Jebel	Arabic word for mountain.
Jue/Jye	The Nilotic ethnic group that resides in the Kasangor Hills/Jebel Kasangor in Boma National Park, within the Greater Pibor Administrative Areas.
Khor	Arabic word for watercourse or drainage channel.
Low land	Land lying near the toic/permanent Sudd.
Machar Marshes	The marshland and swamps, lying north of the Sobat and East of the White Nile, and flooded by inflow from torrents from the Ethiopian uplands and overspills from the rivers of Sobat, Pibor and Baro.
Mundari	A Nilotic ethnic group in South Sudan.
Murle	A Surmic-speaking ethnic group in South Sudan.
NBI	Nile Basin Initiative.
Nuer	A Nilotic ethnic group in South Sudan and Ethiopia.
Nvivo	A software program used for qualitative and mixed-methods research.
Payam	Three second-lowest administrative division, below a county.
POC site	Protection of civilians (PoC) sites.

Rieem	A Dinka word, used to describe the magnitude of the 2019-2024 flood, a massive force that destroys everything indiscriminately.
Shilluk	A Nilotic ethnic group that resides along the bank of the White Nile in South Sudan.
State	One of the ten administrative units in South Sudan.
Sudd	From the Arabic root, to block, the Sudd has come to mean barrier. The word is used loosely to describe the whole area of swamp through which the White Nile system (here the Bahr el Jebel and the Bahr el Zeraf) flows.
Sudd eastern plain	The rain-flooded grasslands east of the Sudd/Bahr el Jebel/White Nile.
Sudd Nile	The "Sudd Nile" is introduced in this thesis as an analytical designation for the reach of the White Nile system extending from Mongalla (the upstream entry point into the Sudd wetland) to Malakal (the downstream exit of the Sudd wetland system).
Sudd western plain	Rain-flooded grasslands west of the Sudd/Bahr el Jebel/White Nile.
Toic	Pronounced toich- common Nilotic word that describes Sudd/river-flooded grasslands to which people and livestock migrate in the dry season.
UNEP	United Nations Environmental Programme.
UNDRR	United Nations Office for Disaster Risk Reduction.
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs.
WFP	World Food Programme.

CHAPTER 1

1 INTRODUCTION

1.1 Background and context of the study

Flood risk is emerging as one of the most significant and systemic environmental challenges of the 21st century, particularly in low- and middle-income countries where high exposure intersects with limited adaptive capacity. Recent global assessments estimate that approximately 1.81 billion people are exposed to significant flood hazards under extreme events, with a disproportionate concentration in developing regions where institutional, financial, and infrastructural constraints amplify vulnerability (Rentschler et al., 2022; World Bank, 2023). The increasing recognition of flood risk as a systemic challenge reflects the interaction between changing hydro-climatic processes, expanding human settlements in exposed areas, and persistent inequalities in adaptive capacity (IPCC, 2022; UNDRR, 2022). In such contexts, flood events are not isolated shocks, but catalysts of long-term socio-economic disruption, often eroding livelihoods, deepening poverty, and triggering displacement (Hallegatte et al., 2016; Internal Displacement Monitoring Centre [IDMC], 2023).

The impacts of flooding operate across multiple, interconnected dimensions. At the immediate level, floods result in loss of life, damage to infrastructure, and destruction of productive assets. At broader scales, they disrupt agricultural systems, undermine food security, and destabilize rural economies (IPCC, 2022; FAO, 2021). Critically, these impacts are mediated by social and institutional conditions, meaning that similar hazard levels can produce markedly different outcomes depending on local vulnerability and adaptive capacity (Macharia et al., 2023; Memon, 2020). This reflects the broader understanding of disaster risk as a product of the interaction between hazard, exposure, vulnerability, and capacity rather than hazard magnitude alone (Wisner et al., 2004; Cardona et al., 2012). This has led to a growing recognition that flood risk is fundamentally a socio-hydrological problem, requiring integrated analysis of both environmental processes and human systems (Sivapalan et al., 2012; Pande and Sivapalan, 2017).

Wetlands and floodplains represent a particularly important, yet understudied, dimension of global flood risk. These environments support human wellbeing through ecosystem services including water regulation, fisheries, agriculture, grazing resources, and biodiversity conservation (Millennium Ecosystem Assessment, 2005; Ramsar Convention, 2018). Their ecological productivity has historically attracted human settlement, resulting in dense populations located directly within dynamic hydrological systems (Junk et al., 2013).

However, this proximity to water creates a structural exposure to flooding. Recent spatial analyses show that population growth in flood-prone areas is outpacing global averages, driven by both demographic pressures and livelihood dependence on floodplain resources (Jongman

et al., 2012; Rentschler et al., 2022). Floodplain occupation therefore represents a persistent human–environment trade-off, where populations benefit from fertile soils, fisheries, transport pathways, and ecosystem services while simultaneously experiencing recurrent flood hazards (Di Baldassarre et al., 2018; Ward et al., 2020). This creates a fundamental tension: wetlands simultaneously sustain livelihoods and expose populations to recurrent hazards.

At the same time, climate variability and change are altering hydrological regimes, including shifts in rainfall intensity, seasonality, and upstream flows (Borgomeo et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) identifies increasing risks from heavy precipitation extremes in many regions, although the magnitude and direction of change vary considerably across climatic zones and river basins (IPCC, 2021). While evidence suggests that extreme hydrological events may be increasing in some regions, the impacts on wetlands are highly heterogeneous, shaped by complex interactions between climate drivers, basin-scale hydrology, and local ecological processes (Nicholson, 2017; Berghuijs et al., 2017). As a result, the relationship between climate change and flood risk in wetland systems remains uncertain and spatially variable rather than uniformly deterministic (Blöschl et al., 2019).

Despite significant advances in global flood modelling, a critical gap persists in the representation of wetland environments and their populations. Most global flood risk assessments have focused on urban areas and economically valuable assets, reflecting the priorities of insurance, infrastructure planning, and economic risk assessment frameworks that have historically shaped model development (Bernhofen et al., 2021; Hirabayashi et al., 2021). Consequently, rural and subsistence-based landscapes—where losses may involve ecosystem services, livestock, social networks, and cultural assets rather than conventional economic

indicators—remain comparatively less visible in global risk assessments (Hallegatte et al., 2016; Ward et al., 2020). Consequently, regions characterized by low asset values—such as rural wetlands—remain underrepresented.

This limitation is compounded by the technical challenges of modelling wetlands. Unlike river channels or urban floodplains, wetlands are hydrologically complex systems characterized by low gradients, dense vegetation, and diffuse flow pathways. These features introduce significant uncertainty into hydraulic modelling, making it difficult to accurately estimate flood extent, depth, and duration (Trigg et al., 2016; Fu et al., 2020). Remote sensing has improved the ability to observe wetland inundation dynamics, but challenges remain in translating satellite-derived observations into accurate estimates of flood depth, duration, and population exposure (Schumann and Bates, 2018; Huang et al., 2018).

As a result, two key gaps emerge in the literature: first, hazard uncertainty characterized by limited accuracy in modelling flood dynamics in wetland systems; and second, exposure uncertainty, emanating from lack of reliable estimates of populations living within these dynamic flood regimes. These uncertainties are particularly pronounced in regions with limited hydrometric networks, weak statistical systems, and scarce historical records, where conventional flood risk assessments often rely on incomplete environmental and demographic information (Trigg et al., 2016; Tellman et al., 2021). These gaps mean that millions of wetland-dependent populations remain effectively "invisible" in global flood risk assessments.

While exposure mapping has improved at global scales, far less is understood about how exposed populations experience, respond to, and adapt to flood risk—particularly in rural and data-scarce environments. In floodplain systems, livelihoods are closely tied to seasonal

hydrology, meaning that flooding is not only a hazard but also a resource that shapes agricultural cycles, grazing patterns, and mobility strategies. Research on floodplain societies demonstrates that communities often develop complex adaptation practices that incorporate seasonal mobility, livelihood diversification, and ecological knowledge rather than simply seeking to eliminate exposure to water (Lebel et al., 2010; Liao, 2012). Traditional coping mechanisms—such as seasonal migration, livelihood diversification, and settlement adjustments—have historically enabled communities to live with hydrological variability. However, increasing flood intensity, frequency, and duration may be pushing these adaptive systems beyond their limits (Godde et al., 2021; Ndebele and Zenda, 2023).

A key limitation in existing research is the lack of dynamic, empirically grounded understanding of human–flood interactions, including: (i) how exposure translates into livelihood impacts; (ii) how communities adapt over time; and (iii) how extreme events reshape mobility patterns and social systems. This limitation is particularly evident in rural floodplain environments, where migration, livelihood change, and ecological adaptation are often studied separately despite being deeply interconnected processes (Black et al., 2011; McLeman, 2014). This last gap is particularly important for understanding displacement and migration, which are increasingly recognized as central components of climate risk but remain poorly quantified in floodplain contexts (IDMC, 2023; Rigaud et al., 2018).

1.2 Motivation for the Study: The Sudd wetland, a critical but understudied system

South Sudan is located within the Greater Horn of Africa (GHA), which comprises of eleven countries with a total population of 375 million in 2020, projected to exceed seven hundred million by 2050 (United Nations, 2022). South Sudan is one of the world's most fragile states and one of the least developed countries in the world (UNEP, 2018). Approximately 97.5% of South Sudan's land area is within the Nile Basin. About 20 percent of the Nile Basin's lies within South Sudan, and 7 percent of that is covered by the Sudd wetland, making it regionally significant and an important part of the Nile Basin water network (NBI, 2020).

The GHA exemplifies the complexity of climate–hydrology–society interactions (Figure 1). Hydroclimatic variability in East Africa is characterized by pronounced spatial and temporal fluctuations in rainfall, driven by the interaction of regional atmospheric dynamics and large-scale ocean–atmosphere processes. This variability is strongly modulated by global climate interactions, particularly the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which influence sea surface temperatures, atmospheric circulation, and moisture transport across the region (Gebremeskel Haile et al., 2023). In recent decades, shifts in these dynamics have contributed to emerging trends such as declining long rains and intensifying short rains, alongside more frequent extremes including droughts and floods, highlighting the complexity and growing unpredictability of East Africa's hydroclimate under climate change (Dunning et al., 2016).

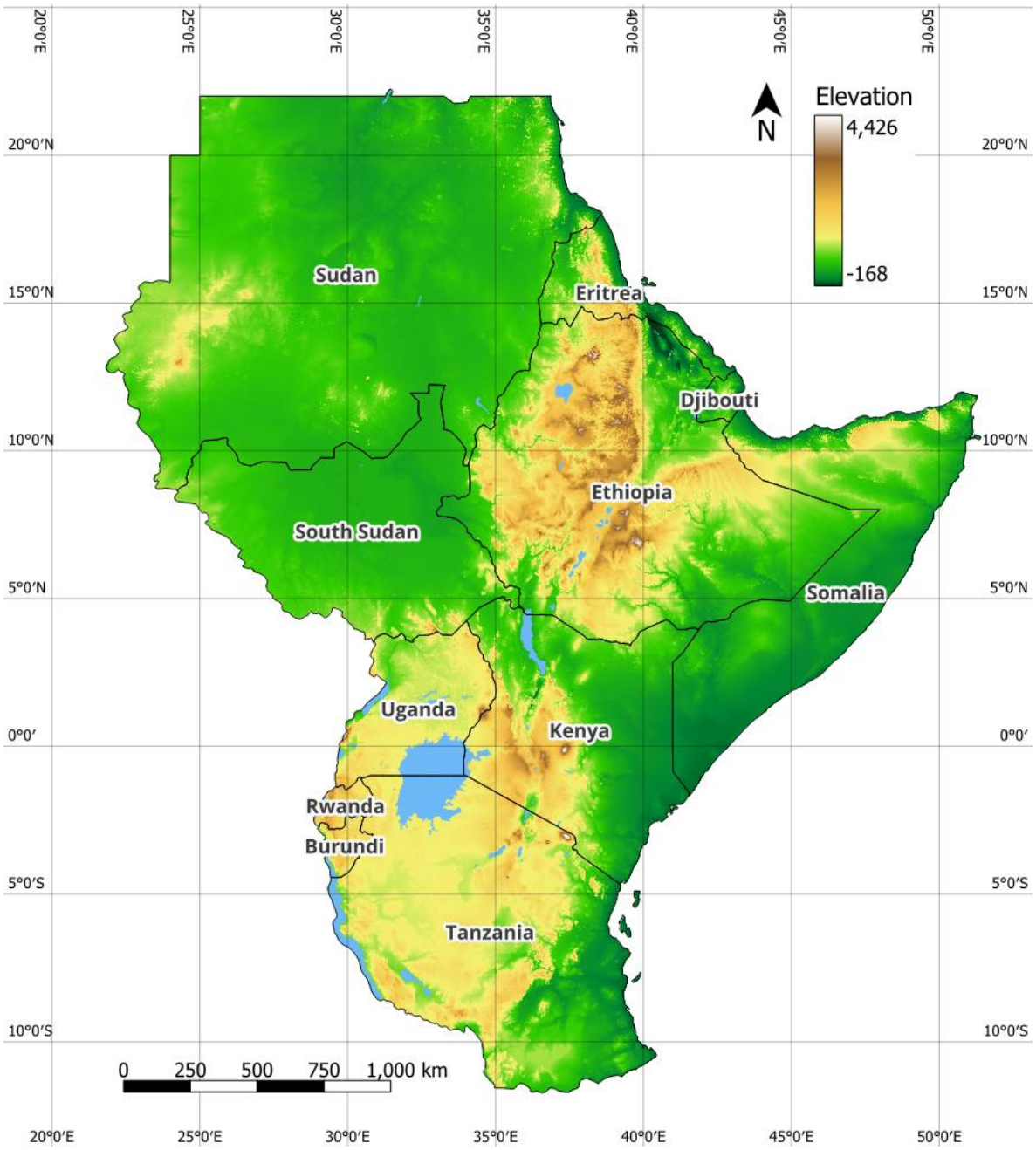


Figure 1: Location of South Sudan within East-Central Africa, showing its position relative to neighboring countries.

While some studies suggest increasing rainfall extremes in parts of East Africa, others emphasize the dominant role of natural variability, highlighting ongoing uncertainty regarding long-term climate trends (Nicholson, 2017; Tierney et al., 2015). This uncertainty complicates

efforts to attribute recent flood events to climate change and underscores the need for regionally grounded, process-based analyses.

Within this regional context, the Sudd wetland of South Sudan represents one of the largest and most complex floodplain systems in the world. Covering a significant portion of the White Nile basin, the Sudd plays a critical role in regional hydrology while supporting millions of people through agriculture, fishing, and pastoralism. The Sudd's hydrology is shaped by a combination of upstream inflows, local rainfall, and extensive wetland storage processes. This creates a highly dynamic flood regime characterized by seasonal inundation and multi-year variability. Historical records indicate that large-scale flooding has occurred repeatedly over the past two centuries, suggesting that extreme events are not unprecedented (Johnson, 1992). However, recent floods (2019–2024) have been exceptional in their spatial extent and persistence, raising questions about whether they represent natural variability or a shift in the hydrological regime. At the same time, South Sudan's socio-political context—including conflict, limited infrastructure, and weak institutional capacity—significantly constrains both data availability and adaptive responses. As a result, the Sudd is one of the most data-scarce and least understood floodplain systems globally.

1.3 Definition of the key concepts

As this research sits at the intersection of multiple disciplines, key terms often carry overlapping or competing meanings (Figure 2).



Figure 2: Adapted from IPCC (2012) and UNDRR (2017): Risk conceptualized as the intersection of hazard, exposure, and vulnerability, extended here to include resilience and community dynamics.

To ensure analytical precision, the following definitions establish a consistent framework for how hazards, exposure, vulnerability, risk, resilience, and community are applied within the specific scope of this study.

Hazard: Hazard refers to the potential occurrence of climate-related physical events or trends that may cause damage and loss. Referring to a climatic event or trend as a "hazard" thus relies

on an assessment of the potential consequences of this climatic change, not simply an assessment of the observed or projected change in a climate variable on its own (IPCC, 2020).

Exposure: Exposure refers to the inventory of elements in an area in which hazard events may occur (Cardona, 2003; UNISDR, 2004 & 2009b). Hence, if population and economic resources were not located in potentially dangerous settings, no problem of disaster risk would exist (IPCC, 2012).

Vulnerability: The concept of vulnerability refers to the predisposition of being adversely affected, and it includes both the sensitivity and susceptibility to harm, as well as the capacity to cope or adapt (Brouwer et al., 2007; IPCC, 2021).

Risk: The concept of risk, as defined by the Intergovernmental Panel on Climate Change (IPCC, 2020), involves the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. Climate risk results from the interaction of hazard, exposure, and vulnerability (IPCC, 2021), and can arise from potential impacts of climate change as well as human responses to climate change.

Resilience: The International Panel on Climate Change (IPCC, 2014b) defines resilience as the capacity of social, economic and environmental systems to cope with a hazardous event, trend or disturbance, responding or re-organizing in ways that maintain systems' essential function, identity, and structure while also maintaining the capacity for adaptation, learning and transformation.

Impact: UN Office for Disaster Risk Reduction (UNDRR) defines disaster impact as the total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and

environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being.

Community: UN Office for Disaster Risk Reduction (UNDRR defines a community as a group of people living in the same place or sharing common characteristics, interests, or identities, and who may be exposed to similar hazards; UNDP (United Nations Development Programme) defines a community as a group of people who share a common space, identity, or organization, often linked by social ties, livelihoods, and institutions.

Mobility: Mobility refers to the capacity, practice, and outcomes of movement across space and within social systems, shaped by environmental, economic, and political constraints (Sheller and Urry 2006; Cresswell 2006; de Haas 2010).

1.4 Core knowledge gaps

Building on the literature above, four interrelated research gaps emerge:

1. Flood hazard characterization gap. There is no comprehensive, spatially explicit understanding of flood hazard dynamics across the Sudd, particularly under extreme conditions.
2. Population exposure gap. The distribution and magnitude of human exposure to flooding remain largely unknown due to the absence of integrated hazard–population datasets.

3. Human adaptation dynamics gap. There is limited empirical evidence on how communities in the Sudd adapt to flooding, including how traditional mobility and livelihood systems are evolving under increasing flood stress.
4. Future risk and migration gap. It remains unclear whether recent extreme floods represent transient anomalies or a regime shift, and how such changes may influence future migration and displacement patterns.

These gaps are not independent; rather, they form a linked chain from hazard → exposure → impact → response, which is currently fragmented in the literature.

To address these gaps, this study proposes three research questions, each corresponding to one of the three core empirical chapters (Chapters 4, 5, and 6). The first question focuses on the first two gaps, while the subsequent questions address the third and final gaps, respectively.

Research question 1: What is the extent of population exposure to flood hazards across the Sudd region?

Specific objectives: There are two objectives in this section, both corresponding to the research question identified above. The first objective is to use outputs from Global Flood Models (GFMs) to map flood hazards across the Sudd region, accounting for spatial heterogeneity in the depths and extents of those hazards. The second objective is to model population distribution and density, quantifying exposed populations across the Sudd region.

Research question 2: How does recent extreme flooding (2019-2024) influence migration and perception of changes in the frequency and severity of flooding in the Sudd region?

Specific objectives: The primary objective of this section is to understand the impact of recent extreme flooding (2019-2024) on human adaptation, thereby guiding policy and investment strategies for the Sudd region. It further investigates the specific ways in which extreme floods disrupt livelihoods and social systems, driving migration in the Sudd region.

Research question 3: How are dynamic migration patterns influenced by flood extent and how may they change in the context of more severe future flooding?

Specific objectives: These objectives are organized to follow the format of the two research questions enumerated above: (i) To address the extent of high impact flood risk and resulting population exposure in the counties assessed, including those of migration origins and destination locations; and (ii) To derive migration rules from the field visits to develop migration flows in the selected counties in the Sudd region, considering the extent of population exposure under climate change scenarios.

1.5 Research aims and design

This study examines flood risk in the Sudd wetland of South Sudan, one of the world's largest and most complex floodplain systems, yet also one of the least understood. The central argument of this thesis is that flood risk in such environments cannot be adequately understood through hazard or exposure analysis alone but requires an integrated socio-hydrological

perspective that explicitly links environmental processes with human responses. This thesis addresses these gaps through an integrated socio-hydrological framework that combines hazard modelling, exposure analysis, and empirical investigation of human responses. The central aim is to develop a comprehensive understanding of flood risk in the Sudd by linking physical flood dynamics with social vulnerability and adaptation processes. To achieve this, the research is structured around three interconnected components:

1. Hazard and exposure mapping. Quantifying the spatial distribution of flood hazards and exposed populations.
2. Empirical analysis of human adaptation. Investigating how communities respond to flood risk, with particular focus on mobility and livelihood strategies.
3. Future risk and migration modelling. Projecting how flood regimes and human responses may evolve under changing climatic conditions.

The first research question is answered using a comprehensive mapping of flood hazards and quantification of population exposed to these hazards in the Sudd region. However, results from these assessments are static as they fail to capture unique dynamics of the population mobility in the Sudd region, which is characterized by rapid change in local populations. The second research question thus builds on the limitation of global products in the context of the Sudd by using a field study to understand human adaptation dynamics to changes in flood hazards and environment. However, analyses of migratory behavior in response to the impacts of extreme flooding only investigate historically observed relationships, which are not necessarily reflective of future migration patterns in the Sudd region. The third research question builds on both the first and second research questions. That question focuses on some of the most

vulnerable and exposed communities to flood hazards identified in Chapters 4 and 5 and assesses how future migration flows among these communities may change under extreme climate (Chapter 6), which addresses the response gap identified in the field study (Chapter 5). To follow is an overarching methodological representation, an overview of these data sources, and the methods taken to achieve the aims of the thesis (Figure 3).

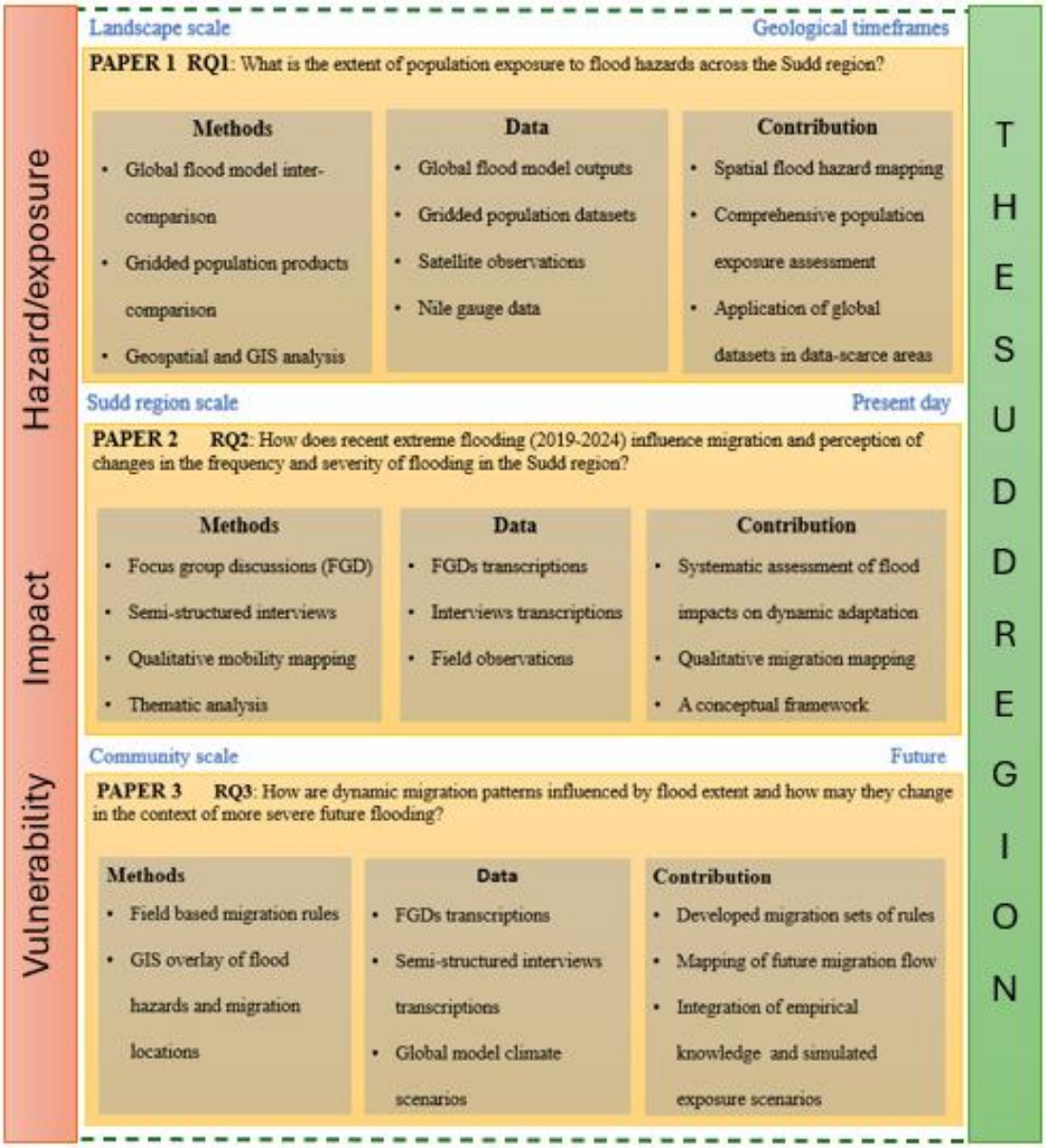


Figure 3: Overarching methodological approaches for addressing the aims for the study.

The thesis uses multimethod approaches, including model intercomparison of GIS geospatial analysis of multiple global flood model hazard and satellite Earth observation flood hazards (Figure 3). The details of the methods and datasets used are further described in each of the three substantive chapters, structured around three principal research questions, each addressed through a dedicated empirical chapter formatted as a journal paper.

1.6 Outline of the thesis structure

This thesis adopts an integrated (thesis-by-publication) format, in which the core empirical chapters are presented as standalone journal articles. This approach is particularly appropriate given the interdisciplinary nature of the research and the urgency of advancing policy-relevant knowledge on flood risk in the Sudd region of South Sudan. In a context characterized by acute climate vulnerability, data scarcity, and ongoing socio-political instability, the timely dissemination of findings through peer-reviewed publications is essential to inform both academic debate and practical resilience planning. To ensure coherence, the thesis includes standalone chapters on the introduction, literature review, and the study area, which provide the overarching theoretical, methodological, empirical, and analytical foundations for the empirical papers.

Following the introductory chapter, **Chapter 2** provides a literature review of existing works that underpin this thesis. The chapter is separated into a conceptual literature review and methodological literature review. The conceptual literature review explores concepts such as the socio- hydrology, resilience, transformative adaptation, and ecosystem services as they inform the thesis. The methodological literature review highlights the key advances in

methodologies relevant to dynamics of flooding, including global flood modelling and population modelling. Methodological review also covers the application of satellite observation such as remote sensing. The literature review identifies and justifies the four interrelated key gaps, providing the background and justification for incorporating multiple approaches in this thesis to answer the research questions.

Chapter 3 addresses the research study area by situating the Sudd in South Sudan within the Nile basin system and comparing the Nile's characteristics with those of major rivers worldwide. The chapter then delineates the Sudd region as both a specific geographical location and a subject matter of this thesis, providing overviews of its unique geographical features, climatological conditions, and physical characteristics of the land, soil, and vegetations. The chapter unpacks the ecological paradox of the Sudd, contrasting its geopolitical back drop with the benefits of its ecosystem services to the local communities. The chapter subsequently covers literature of East African climate, the hydrology of the Sudd, Sudd regional hydro-climatic role in the Nile system, the water balance of the Sudd wetland, flooding history, human vulnerability and exposure. Lastly, the chapter explores socio-economic situation in the Sudd: history and hydro-politics and reviews the Sudd as a socio-hydrological system.

Chapter 4 presents a geospatial analysis of population exposure to flooding in the Sudd, quantifying the scale and spatial distribution of risk. The chapter addresses the first research question by using gridded global datasets in lieu of the census data to provide the first comprehensive flood mapping and exposure for the Sudd region. The chapter uses satellite observations of flood extent to corroborate the results of global model intercomparison, before analyzing population exposures among the multiple georeferenced population products. The fifth chapter starts with literature overview of human-flood dynamics around the wetlands

across the world, before describing specific details of the hydrological conditions and unique ecosystems of the Sudd. The chapter explores varying adopted boundaries for the Sudd and presents historical report of major floods that occurred in the Sudd region over the last two centuries. Lastly, the chapter presents the results, before it concludes with the discussions and conclusion.

Chapter 5 examines the dynamics of human adaptation to flood risk, drawing on socio-hydrological perspectives to analyze behavioral responses and coping strategies. The chapter builds on the known limitation of the global gridded datasets in previous chapter and addresses the second research question by focusing on field study on the changing dynamics of human adaptations. The chapter describes the field data acquired through a multi-method approach, including focus group discussions and semi-structured interviews, participatory mapping, and field observations. The chapter assesses hydrologically hazardous and vulnerable areas identified in the previous chapter and evaluates how communities cope with and adapt to riverine hazards, including flood-induced migration responses. This chapter covers a literature overview of human adaptations to extreme flooding (2019-2024), Sudd study area including changes in transhumance (movement of pastoralists with cattle) and level of flood-induced population migration. The chapter advances a conceptual framework and describes methodological steps for qualitative data analysis of the field data, before presenting key results, discussions, implications, and conclusion

Chapter 6 investigates the relationship between flood risk and migration, providing both a historical and climate change-informed assessment of displacement patterns. The chapter addresses the third research question by using field-data derived migration rules to characterize migration flows across and out of the Sudd region. The chapter assesses the impacts of the

simulations of multi-return flood risk and resultant population exposure scenarios in the counties assessed during the field study. The chapter presents a brief literature review on migration, bringing previous research understanding to the Sudd migrations responses to increasing flooding. The chapter describes sets of predictive rules that inform migration flows in the Sudd region. It then maps changes in migration flows in the Sudd region in response to the migration rules and exposure scenarios under climate change, before presenting the results and analysis, discussions, recommendations for the Sudd region, and conclusion.

In summary, the last three chapters form a coherent analytical progression from exposure, to adaptation, to mobility, unified through a common study area, methodological framework, and conceptual grounding in Socio-hydrology. The integrated format enables each chapter to make an independent scholarly contribution while also forming part of a cumulative argument developed across the thesis. All three empirical chapters have been published or under review in peer-reviewed journals, ensuring that the research meets established standards of academic rigor and contributes to ongoing international discourse on flood risk and climate adaptation. This integrated structure reflects the central premise of the thesis: that understanding flood risk in the Sudd requires a multi-dimensional and scalable analytical approach, capable of linking environmental processes with human responses in a rapidly changing socio-hydrological system.

The final discussion and conclusion, **Chapter 7** synthesizes the findings across all components, drawing out collective implications for flood risk management approaches in dynamic wetland systems. The chapter discusses the summary of the thesis, key findings, and research contributions, including a conceptual contribution on human-flood dynamics, a methodological

contribution on integrating empirical data and flood hazard and exposure mapping, and a contextual contribution. The chapter provides context-based policy recommendation and highlights their implications for decision-making at various scales including Nile Basin regional level, South Sudan national-scale, Sudd regional level and community level. The chapter offers more critical implications for the Sudd region, including weighing the status of the current state, exploring possible forced migration and planned migration. The conclusion identifies main limitations, expounding on opportunities for improved conceptualizations and opportunities for advancing methodologies. The thesis concludes by outlining key directions for future research and offering brief overarching remarks that integrate the central threads of the study conducted in the Sudd.

(*References for Chapters 1–3 and Chapter 7 are provided at the end of the thesis, while references for the main analytical chapters (Chapters 4–6) are listed at the end of each respective chapter*)

CHAPTER 2

2 LITERATURE REVIEW

This chapter provides a review of existing literature on the main conceptual and methodological developments and research gaps that guide the development of this thesis. The conceptual literature review addresses the concepts, explores their connections, and identifies gaps in current understanding of the Sudd human-flood dynamics. The methodological review summarizes and evaluates the state of relevant research methods used in the study. For further review of literature on GIS analysis of global flood modelling and population exposure modelling, field study of the dynamics of human adaptation, and estimation of migration flows under future climate scenarios in the Sudd region, refer to Chapters 4, 5, and 6, respectively. Flood-related migration is a recognized global phenomenon, defined and described with a variety of terms (see Table 1), driven by the increasing frequency and intensity of flood events.

Table 1: Glossary of the terms used to define people's migration and displacement and the environmental dimension of these phenomena (Wolde et al., 2023).

Term	**Definition**	**Source**
Displacement	The movement of a person who has been forced to flee their place of residence to avoid the consequences of violence, armed conflict, and natural or human-made disasters.	(Deng, 1998)
Migration	The movement of persons away from their place of usual residence, either across an international border or within a State, temporarily or permanently and for a variety of reasons.	(IOM, 2019)
Emigration	From the perspective of the country of departure, the act of moving from one's country of nationality or usual residence to another country, so that the country of destination effectively becomes the new country of usual residence.	(IOM, 2019)
Immigration	From the perspective of the country of arrival, the act of moving into a country other than one's country of nationality or usual residence, so that the country of destination effectively becomes the new country of usual residence.	(IOM, 2019)
Disaster displacement	The movement of persons who have been forced or obliged to leave their homes or places of habitual residence because	(IOM, 2019; Kälin, 2015)

	of a disaster or to avoid the impact of an immediate and foreseeable natural hazard.	
Forced migration	A migratory movement which, although the drivers can be diverse, involves force, compulsion, or coercion.	(IOM, 2019)
Climate migration (working definition)	The movement of a person or groups of persons who, predominantly for reasons of sudden or progressive change in the environment due to climate change, are obliged to leave their habitual place of residence, or choose to do so, either temporarily or permanently, within a State or across an international border.	(Chazalnoël and Ionesco, 2016; IOM, 2016)
Migrants	A person who migrates.	(IOM, 2019)
International migrant	Any person who changes his or her country of usual residence, excluding movements that are due to recreation, holiday, visits to friends and relatives, business, medical treatment, or religious pilgrimages.	UN DESA (1998)
Internally displaced persons (IDPs)	Persons or groups of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular because of or to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human-made disasters, and who have not crossed an internationally recognized State border.	(Deng, 1998; IOM, 2019)

Climate/environmental refugee	A category of environmental migrants whose movement is clearly of a forced nature. Individuals forced to leave their country because of environmental or climatic processes or events would not necessarily meet the definition of a refugee under the Convention and Protocol Relating to the Status of Refugees (1951). Most of those who flee environmental degradation or disaster, including when due to climate change, do not cross an international border, which is an additional requirement for the application of the refugee definition.	(Mcadam, 2009)

2.1 Conceptual literature review

The first section of the literature review focuses on the conceptual advances that have shaped the overall research questions and objectives in this thesis. This conceptual literature review therefore begins with a brief history of the concept of socio-hydrological dynamics and the key advances and applications that have accelerated this field, particularly in wetland floodplains (Section 2.1.1). Subsequently, the chapter addresses ecosystem services review in the context of historical and current dynamics of human exposure (2.1.2), before reviewing transformative adaptation (2.1.3) Lastly, the chapter reviews resilience to flood risk in floodplain contexts (2.1.4), before outlining the key conceptual gaps that this thesis aims to address.

2.1.1 Socio-hydrological field

This thesis is informed by conceptual approaches that link hydrological change with societal vulnerability. Hydrology research has progressively evolved from a focus on physical processes within the natural water cycle toward integrated frameworks that explicitly incorporate human–water interactions (Jaramillo and Destouni, 2014; Piemontese et al., 2024). Within this shift, socio-hydrology has emerged as an interdisciplinary field concerned with dynamic interactions and feedback between social and hydrological processes (Di Baldassarre et al., 2015).

Socio-hydrology has been described as "a new science of people and water," aimed at understanding the co-evolution of coupled human–water systems (Sivapalan et al., 2011). Foundational work in the field emphasizes reciprocal interactions, feedback loops, and emergent dynamics between hydrological processes and human responses (Di Baldassarre et al., 2013; Di Baldassarre and Montanari, 2012; Drake, 2017; Mao et al., 2017; Sivapalan et al., 2012). These interactions are increasingly important in the context of intensified hydrological extremes, such as flooding, and growing anthropogenic influences on the water cycle (Blöschl et al., 2019; Montanari et al., 2013).

A key contribution to the field is the development of conceptual and dynamic models that represent feedback between hydrological and social processes. For example, Di Baldassarre et al. (2013) demonstrate how human–flood systems exhibit reciprocal effects and emergent patterns, showing that societal responses can alter flood dynamics and vice versa. Socio-

hydrological modeling has further distinguished between different societal adaptation pathways, including “green societies,” which adapt by relocating away from flood-prone areas, and “technological societies,” which rely on engineered solutions such as levees and dikes (Di Baldassarre et al., 2015).

The intellectual roots of socio-hydrology can be traced to earlier work on co-evolutionary dynamics in human–environment systems. Studies such as Di Baldassarre et al. (2012), Geels (2005), and Kallis (2010) examine long-term trajectories of water–society interactions, including technological development and resource management in both contemporary and historical contexts. Wesselink et al. (2017) highlight that while socio-hydrology has gained prominence within the natural sciences, it parallels a longstanding tradition in the social sciences that conceptualizes water as both a natural and social construct. They argue for complementarity between these traditions rather than epistemological conflict.

Resilience has become a central analytical lens within socio-hydrology. Mao et al. (2017) propose a framework that conceptualizes resilience in coupled human–water systems across three dimensions: absorptive, adaptive, and transformative capacities. This aligns with broader system-based perspectives that interpret socio-hydrological systems as complex, adaptive systems characterized by nonlinear dynamics and feedback. Winder et al. (2005) further connect co-evolutionary theory to complex systems research, emphasizing the importance of adaptability and dynamic change. Similarly, Sivapalan and Blöschl (2015) argue for a co-evolutionary perspective in hydrology, highlighting the role of changing human values as intrinsic drivers of system dynamics. The broader resilience literature further supports this

framing, particularly the conceptualization of resilience as the capacity of systems to absorb disturbance, adapt, and transform (Holling, 1973; Folke, 2006).

A defining feature of socio-hydrology is the treatment of humans as endogenous components of the water cycle. Human activities — including water consumption, land use change, pollution, and governance interventions — are understood as integral to hydrological processes (Sivapalan et al., 2011). This perspective foregrounds the importance of feedback mechanisms operating across spatial and temporal scales, which can generate emergent behaviors and, in some cases, lead to tipping points and regime shifts (Sivapalan et al., 2012; Winder et al., 2005; Kallis, 2010). These system dynamics are consistent with broader literature on complex adaptive systems and socio-ecological regime shifts (Folke, 2006; Holling, 1973).

Importantly, socio-hydrology also recognizes the inherent uncertainty and unpredictability of coupled systems. Nonlinear interactions between human and hydrological processes can produce unexpected outcomes or "surprises" (Gordon et al., 2022), complicating prediction and long-term planning (Sivapalan et al., 2011). These dynamics are particularly relevant in the context of extreme events, where rare but high-impact occurrences—sometimes conceptualized as "Black Swan" events (Taleb, 2007)—can have profound socio-economic consequences (Mao et al., 2017). The challenge of predictability in such systems has been widely recognized in flood hydrology and risk science, particularly in relation to non-stationarity and deep uncertainty (Blöschl et al., 2019).

Overall, the socio-hydrological literature marks a paradigm shift toward integrated analyses of human–water systems. It emphasizes co-evolution, feedback, emergent dynamics, and

resilience, providing a robust framework for understanding the interplay between hydrological processes and societal change.

Conceptual framing of this study

Building on these theoretical foundations, this study adopts a socio-hydrological perspective to examine the co-evolution of flooding and human systems. It conceptualizes flood–society interactions as nonlinear, dynamic processes characterized by feedback across spatial and temporal scales. The analysis focuses on how hydrological extremes interact with social systems to produce emergent outcomes, including migration, adaptation, and transformations in vulnerability. Attention is given to resilience as a multidimensional property—encompassing absorptive, adaptive, and transformative capacities—and to how these capacities evolve in response to repeated flood exposure (Folke, 2006; Mao et al., 2017).

In line with socio-hydrological theory, the study treats human responses—such as mobility, settlement decisions, and livelihood adaptation—as endogenous components of the system. It therefore seeks to identify feedback mechanisms between flood dynamics and societal change, as well as potential tipping points that may lead to new system states (Di Baldassarre et al., 2013; Sivapalan et al., 2012). Given the inherent uncertainty and potential for surprise in such systems, the study does not aim for precise prediction but rather for an improved understanding of system trajectories and emergent dynamics, particularly in the context of extreme flood events (Gordon et al., 2022; Blöschl et al., 2019).

2.1.2 Ecosystem services review

Ecosystem services (ES) literature provides a conceptual framework for understanding how natural systems sustain human well-being, particularly in complex environments such as floodplains. As dynamic socio-ecological systems characterized by periodic inundation, high ecological productivity, and dense human settlement, floodplains exemplify the multifunctionality emphasized in ES research (Millennium Ecosystem Assessment, 2005; Fisher et al., 2009). Floodplains are widely recognized as socio-ecological systems where hydrological variability, ecological productivity, and human land use interact to generate multiple ecosystem services (Tockner & Stanford, 2002; Junk et al., 1989). The concept of ecosystem services—defined as the benefits humans derive from ecosystems—has become central to understanding the multifunctionality of floodplains and their role in mediating flood risks and human exposure (Millennium Ecosystem Assessment, 2005; Costanza et al., 1997). This literature review synthesizes key debates on (i) the types and functions of ecosystem services in floodplains, (ii) the effects of flooding regimes on these services, and (iii) the implications for human exposure and risk.

Ecosystem services of floodplains

Floodplains are widely recognized as "hotspots" of ecosystem service provision due to the interaction of hydrological, geomorphological, and ecological processes (Tockner & Stanford, 2002; Mitsch & Gosselink, 2015). They generate provisioning, regulating, supporting, and cultural services that are critical to human well-being (Böck et al., 2018; Mitsch et al., 2005). These include nutrient cycling, carbon sequestration, fertile soils for agriculture, fisheries

production, groundwater recharge, and recreational opportunities (Fisher et al., 2009; Millennium Ecosystem Assessment, 2005).

Regulating services are particularly important in floodplain contexts. Floodplains act as natural buffers that attenuate flood peaks by storing and slowly releasing water, thereby reducing downstream flood risk (Acreman and Holden, 2013; Bullock and Acreman, 2003). Their capacity for sediment and nutrient retention also improves water quality and supports downstream ecosystems. Hydrological connectivity between river channels and floodplain wetlands enhances these functions, emphasizing the importance of lateral exchange processes (Thorp et al., 2010; Erős et al., 2017). These connectivity-driven processes are widely recognized as fundamental to maintaining floodplain ecological integrity (Ward, 1989; Tockner et al., 1998).

At the same time, floodplains provide significant provisioning services that attract human settlement, including fertile agricultural land and water resources. This dual role—as both resource-rich environments and hazard-prone areas—creates inherent tensions in floodplain management (Opperman et al., 2017; Winemiller, 2019). The literature consistently shows that human settlement in floodplains is strongly driven by perceived agricultural and economic benefits despite elevated flood risk exposure (Poff et al., 2011; Opperman et al., 2017).

Flooding regimes and ecosystem service dynamics

Flooding is a fundamental ecological process that sustains floodplain ecosystem services. Seasonal or moderate floods enhance ecosystem functioning by redistributing nutrients, supporting primary productivity, and maintaining habitat diversity (Junk et al., 1989). This "flood pulse concept" is widely recognized as a foundational ecological theory explaining

floodplain productivity and biodiversity (Junk et al., 1989; Bayley, 1995). Empirical studies show that small or regular floods can increase ecosystem service provision, including water regulation, fisheries productivity, and recreation (Talbot et al., 2018).

However, extreme flooding events can disrupt ecosystem processes and degrade services. Large floods often result in losses across multiple ecosystem services, including damage to infrastructure, declines in water quality, and disruption of ecological communities (Talbot et al., 2018). This aligns with broader evidence that disturbance magnitude and frequency are key determinants of ecosystem resilience and service stability (Scheffer et al., 2001; Folke et al., 2004). The distinction between beneficial "ecological floods" and damaging "extreme floods" is therefore critical in the literature.

Hydrological variability — particularly the frequency, duration, and magnitude of floodplain inundation — plays a central role in shaping ecosystem service outcomes. For example, floodplain inundation facilitates sediment deposition and soil fertility, but excessive or prolonged flooding may reduce agricultural productivity and increase exposure to hazards (Scott et al., 2019). Climate-driven changes in hydrological regimes are increasingly recognized as key drivers of ecosystem service uncertainty in floodplain systems (IPCC, 2021; Palmer et al., 2008). Recent research emphasizes the importance of maintaining natural flood regimes to sustain ecosystem services. Alterations through levees, dams, and land-use change often reduce floodplain connectivity, leading to declines in ecosystem service provision and increased vulnerability to extreme flood events (Opperman et al., 2017). Such hydrological modifications are widely documented as major causes of floodplain ecosystem degradation globally (Poff et al., 1997; Nilsson et al., 2005).

Floodplains, ecosystem services, and human exposure

The relationship between ecosystem services and human exposure in floodplains is complex and often paradoxical. On one hand, ecosystem services such as fertile soils and water availability attract human populations, increasing settlement density in flood-prone areas. On the other hand, regulating services—such as flood attenuation and water storage—can reduce exposure and vulnerability. This duality is central to the "risk–benefit" trade-off in floodplain systems. Floodplains simultaneously provide life-supporting services and expose populations to flood hazards (Winemiller, 2019). This paradox has been widely discussed in flood risk literature, which emphasizes that exposure is socially constructed through land-use decisions and economic incentives (Wisner et al., 2004; Adger, 2006).

As a result, human exposure is not merely a function of hazard but is also shaped by the spatial distribution of ecosystem services and the socio-economic value placed on them. Degradation of floodplain ecosystems—through urbanization, agricultural intensification, and river engineering—often leads to the loss of regulating services, thereby increasing flood exposure and risk. For example, the reduction of natural flood storage capacity can amplify downstream flooding, exposing larger populations and infrastructure to hazard impacts (Acreman et al., 2003; Opperman et al., 2017). Conversely, the restoration and conservation of floodplain ecosystems are increasingly promoted as nature-based solutions (NBS) to reduce flood risk while enhancing ecosystem services (Cohen-Shacham et al., 2016; Seddon et al., 2020). These approaches aim to reconcile human use with ecological processes by allowing controlled flooding in designated areas, thereby reducing exposure in high-risk zones while maintaining ecosystem functionality.

Emerging debates and research gaps

Recent scholarship highlights several key debates in the study of ecosystem services in floodplains. First, there is growing recognition of the need to move beyond static assessments of ecosystem services toward dynamic frameworks that account for temporal variability in flooding regimes (Seppelt et al., 2011; Villa et al., 2014). Ecosystem service provision is inherently linked to hydrological dynamics, yet many assessments fail to incorporate this variability.

Second, the integration of ecosystem services into flood risk frameworks remains limited. While conceptual models increasingly acknowledge the role of regulating services in reducing hazard and exposure, empirical quantification of these benefits is still developing (La Notte et al., 2017).

Third, there is a need to better understand trade-offs and synergies among ecosystem services, particularly under conditions of climate change and increasing flood risk. For instance, strategies that maximize agricultural production may reduce flood regulation capacity, thereby increasing exposure (Rodríguez et al., 2006; Raudsepp-Hearne et al., 2010).

Finally, issues of equity and distribution are underexplored. Ecosystem services in floodplains are unevenly distributed, and marginalized populations often experience higher exposure to flood risks while having limited access to the benefits of ecosystem services (Leach et al., 2018; IPCC, 2022).

In summary, the ecosystem services literature demonstrates that floodplains are multifunctional landscapes where ecosystem services play a critical role in shaping both environmental outcomes and human exposure to flooding. Flooding itself is a double-edged process: it sustains ecosystem services under natural regimes but can disrupt them under extreme conditions. The interplay between ecosystem service provision, flood dynamics, and human settlement patterns creates complex trade-offs that are central to floodplain management.

2.1.3 Transformative adaptation review

Transformative adaptation has gained increasing prominence within climate change scholarship as a framework for understanding systemic responses to escalating environmental risks, particularly in highly exposed and dynamic environments such as floodplains (IPCC, 2014; IPCC, 2022). Distinct from incremental or "business-as-usual" adaptation, transformative adaptation refers to fundamental changes in social-ecological systems that alter underlying structures, functions, and feedback in response to climate stressors (Pelling, 2011; Kates, Travis, and Wilbanks, 2012). This distinction between incremental and transformational adaptation is widely established in the adaptation literature, particularly in relation to limits to adaptation under increasing climate risk (Klein et al., 2014; Park et al., 2012). In flood-prone regions, where recurrent inundation intersects with dense human settlement and livelihood dependence on water systems, such transformations often involve shifts in land use, governance regimes, infrastructure design, and even the relocation of populations (Siders, 2019; Hino et al., 2017). These processes are increasingly understood as necessary where existing adaptation

measures prove insufficient under conditions of intensifying flood hazards and rising human exposure (IPCC, 2022; Oppenheimer et al., 2014).

A central concern in the literature is the relationship between transformative adaptation and human exposure in floodplains. Exposure is not simply a matter of geographic proximity to flood hazards but is actively produced through historical settlement patterns, economic marginalization, and policy decisions that concentrate vulnerable populations in risk-prone areas (Adger, 2006; Wisner et al., 2004). This framing is consistent with disaster risk theory, which emphasizes that risk is socially constructed through the interaction of hazard, exposure, and vulnerability (UNDRR, 2015; Blaikie et al., 1994). Floodplains have long attracted human settlement due to their ecological productivity and access to water resources, creating a paradox in which areas of high livelihood opportunity are simultaneously zones of heightened risk (Di Baldassarre et al., 2013). This "attractiveness–risk paradox" has been widely documented in flood risk research, particularly in rapidly urbanizing river basins (Opperman et al., 2017; Poff et al., 2011). As climate change amplifies the frequency and intensity of flood events, these patterns of exposure become increasingly unsustainable, prompting calls for transformative approaches that address root causes rather than symptoms of vulnerability (IPCC, 2022; Pelling, 2011).

The literature further highlights that transformative adaptation is inherently political, involving contested processes of decision-making, resource allocation, and power redistribution. Pelling (2011) emphasizes that transformation requires challenging entrenched institutional and socio-economic structures that perpetuate vulnerability, including unequal access to land, infrastructure, and governance mechanisms. This aligns with broader political ecology

perspectives that frame adaptation as embedded within relations of power and inequality (Robbins, 2012; Eriksen et al., 2015). In floodplain contexts, this may involve difficult and often controversial measures such as managed retreat, resettlement, or the reconfiguration of agricultural and livelihood systems (Hino et al., 2017; Siders, 2019). Such interventions raise critical questions about justice and equity, particularly regarding who bears the costs of transformation and who benefits from reduced risk (Eriksen et al., 2015). The literature on climate justice further emphasizes that adaptation interventions can produce "winners and losers," particularly when displacement or land reallocation is involved (Schlosberg, 2013; Sovacool et al., 2015).

Another key strand of scholarship situates transformative adaptation within broader social-ecological systems thinking, emphasizing nonlinearity, thresholds, and feedback. Kates et al. (2012) argue that transformation becomes necessary when incremental adaptation fails to prevent unacceptable levels of risk, often marked by crossing critical thresholds in environmental or social systems. This threshold-based framing is consistent with resilience and regime shift theory in complex systems science (Scheffer et al., 2001; Walker & Salt, 2006). In floodplains, such thresholds may include the loss of protective ecosystems (e.g., wetlands), repeated infrastructure failure, or the erosion of livelihood viability. These tipping points can catalyze abrupt and large-scale changes, including shifts in settlement patterns or governance frameworks. At the same time, the concept of resilience has been both integrated into and critiqued within transformative adaptation debates. While resilience thinking emphasizes the capacity of systems to absorb shocks and maintain function (Folke, 2006), critics argue that an exclusive focus on resilience may obscure the need for deeper structural change, particularly in contexts where maintaining the status quo perpetuates vulnerability (Brown, 2014). This

critique is widely reflected in debates on "transformability" as a distinct dimension of resilience in social-ecological systems (Walker et al., 2004; Folke et al., 2010).

Recent contributions to literature also explore the pathways and mechanisms through which transformative adaptation occurs. These include policy innovation, institutional reform, technological change, and shifts in social norms and values (O'Brien, 2012). This aligns with transition theory and multi-level governance approaches that emphasize socio-technical system change (Geels, 2011; Meadowcroft, 2009). In floodplain environments, examples range from large-scale river basin reconfiguration and nature-based solutions to community-led relocation and livelihood diversification strategies (Seddon et al., 2020; Cohen-Shacham et al., 2016). Importantly, transformation is increasingly understood as a process rather than an outcome, characterized by experimentation, learning, and negotiation across multiple scales (Olsson et al., 2014). This process-oriented perspective is consistent with adaptive governance frameworks that emphasize learning-by-doing and iterative decision-making under uncertainty (Folke et al., 2005; Pahl-Wostl, 2007).

Despite its conceptual appeal, transformative adaptation remains challenging to operationalize in practice. Barriers include institutional inertia, limited financial resources, and political resistance to disruptive change (Wise et al., 2014). These constraints are widely documented in adaptation governance literature, particularly in low-income and climate-vulnerable regions (Moser & Ekstrom, 2010; Adger et al., 2009). In many floodplain settings, short-term development priorities and governance fragmentation further constrain the adoption of transformative strategies. Moreover, uncertainties associated with climate projections and socio-economic change complicate decision-making, often leading to a preference for

incremental measures that are more immediately feasible but ultimately insufficient (Dessai et al., 2009; Hallegatte, 2009). As a result, there is a growing recognition of the need for integrated approaches that link risk assessment, exposure reduction, and long-term planning within a transformative framework (IPCC, 2022).

In summary, the literature on transformative adaptation in floodplain contexts provides a critical foundation for understanding how societies can respond to escalating flood risks in ways that address underlying drivers of exposure and vulnerability. It highlights the necessity of moving beyond technical fixes toward systemic change, while also drawing attention to the social, political, and ethical complexities inherent in such transformations. As climate change continues to intensify hydrological extremes, advancing this body of scholarship is essential for identifying pathways toward more sustainable and equitable adaptation in flood-prone landscapes.

2.1.4 Resilience review

Resilience has become a foundational concept in examining how human and environmental systems respond to flood risks, particularly in dynamic floodplain settings. Broadly defined, resilience refers to the capacity of a system to absorb disturbances, reorganize, and continue functioning without losing its essential structure and identity (Holling, 1973). This ecological framing has been widely extended across disciplines, particularly in studies of complex adaptive systems and environmental change (Gunderson & Holling, 2002; Walker et al., 2004). Early ecological interpretations emphasized system stability and recovery, but subsequent scholarship expanded the concept to encompass social–ecological systems, highlighting the

interplay between human agency, institutions, and environmental processes (Folke, 2006). In floodplain environments, resilience is therefore not limited to resistance against flooding but includes the ability of communities to adapt, learn, and transform in response to recurring hydrological variability (Walker et al., 2004; Folke et al., 2010).

Within disaster risk reduction literature, resilience is often conceptualized alongside vulnerability and exposure as a critical component of risk (Wisner et al., 2004). This risk framing is consistent with disaster studies that position vulnerability as socially produced through political and economic processes (Blaikie et al., 1994; UNDRR, 2015). While vulnerability emphasizes susceptibility to harm, resilience focuses on the capacities that enable individuals and communities to cope with and recover from flood events. This perspective aligns with the shift from hazard-centric approaches toward people-centered frameworks that prioritize local capacities, knowledge systems, and adaptive strategies (Adger, 2000). In floodplains, where flooding is often seasonal and predictable, resilience is closely tied to long-standing socio-cultural practices such as mobility, flood-based agriculture, and livelihood diversification (Jury & Vaux, 2007; Lantz, 2010).

The integration of resilience into climate change adaptation discourse has further refined its conceptualization. Scholars distinguish between absorptive, adaptive, and transformative capacities, which together shape how communities respond to environmental stressors (Béné et al., 2012). This three-dimensional framing has become widely adopted in climate resilience literature and disaster risk governance (IPCC, 2012; Bahadur et al., 2015). Absorptive capacity refers to the ability to cope with immediate shocks, adaptive capacity involves incremental adjustments to changing conditions, and transformative capacity entails fundamental changes

to social or institutional structures. In floodplain regions, these capacities are evident in practices such as elevated housing, seasonal migration, and shifts in livelihood strategies. However, the extent to which these capacities can be mobilized is often constrained by structural inequalities, governance limitations, and access to resources (Pelling, 2011; Adger et al., 2009; Eriksen & Brown, 2011).

A growing body of literature emphasizes the importance of social–ecological resilience in floodplain systems, where human livelihoods are deeply intertwined with hydrological cycles. Rather than viewing floods solely as hazards, researchers highlight their ecological and economic benefits, such as nutrient deposition and support for fisheries and agriculture (Lebel et al., 2006). This aligns with ecological flood pulse theory, which emphasizes the productivity of natural flooding regimes (Junk et al., 1989; Tockner & Stanford, 2002). This perspective challenges conventional risk management approaches that prioritize flood control and instead advocates for adaptive management strategies that accommodate natural flood regimes (Pahl-Wostl, 2007; Gunderson & Light, 2006). Consequently, resilience in floodplain contexts is increasingly understood as the capacity to live with floods rather than eliminate them (Opperman et al., 2017; Seddon et al., 2020).

Field studies from diverse floodplain regions demonstrate the complexity and variability of resilience. For instance, pastoralist and agro-pastoralist communities often rely on mobility and flexible resource use to adapt to fluctuating water availability, while riverine farmers may adopt flood-recession agriculture and crop diversification (Morton, 2007). Such adaptive livelihood systems are widely documented in dryland and floodplain socio-ecological research (McCabe, 2010; Nassef et al., 2009). These strategies are embedded in local knowledge systems that have

evolved over generations, yet they are increasingly under pressure from climate change, population growth, and infrastructural interventions such as dams and levees. Such interventions can alter flood regimes, sometimes undermine traditional adaptive practices and create new vulnerabilities (Birkmann et al., 2013; Nilsson et al., 2005; Poff et al., 1997).

Despite its widespread use, the concept of resilience has also been critiqued for its ambiguity and normative implications. Some scholars argue that resilience discourse can obscure issues of power, inequality, and justice by emphasizing system persistence over transformative change (Cannon and Müller-Mahn, 2010). This critique is strongly reflected in political ecology and critical geography perspectives on resilience (Davoudi et al., 2012; Reid, 2012). In floodplain contexts, this raises important questions about whose resilience is prioritized and whether adaptation strategies reinforce existing social disparities. As a result, recent literature calls for more critical and context-sensitive approaches that incorporate political, economic, and cultural dimensions into resilience analysis (Brown, 2014; Matyas & Pelling, 2015).

Overall, the literature on resilience in floodplain environments highlights its evolution from a purely ecological concept to a multidimensional framework encompassing social, economic, and institutional factors. It underscores the importance of adaptive capacities, local knowledge, and flexible livelihood strategies in shaping responses to flood risk. At the same time, it reveals ongoing debates about the conceptual clarity and practical application of resilience, particularly in relation to equity and transformation. This review therefore situates resilience as both an analytical lens and a contested concept, central to understanding human adaptation in flood-prone landscapes.

2.1.5 Summary of the conceptual framework review

The conceptual literature review synthesizes four interrelated frameworks that together shape the thesis's analytical approach to floodplain dynamics. First, socio-hydrology provides an overarching framework, emphasizing the co-evolution of human and water systems through feedback, nonlinearity, and emergent dynamics. It reframes humans as endogenous components of hydrological systems and highlights resilience, uncertainty, and tipping points as key features of coupled human–water interactions (Sivapalan et al., 2011; Sivapalan et al., 2012; Di Baldassarre et al., 2013). This systems-oriented perspective is widely situated within broader complex systems theory, which emphasizes feedback-driven co-evolution and regime shifts in coupled human–environment systems (Liu et al., 2007; Walker & Salt, 2006).

Second, the ecosystem services framework conceptualizes floodplains as multifunctional socio-ecological systems that simultaneously generate benefits (e.g., flood regulation, fertile land) and risks (flood exposure). It underscores the dynamic relationship between flooding regimes and service provision, as well as the inherent trade-offs and inequalities shaping human exposure (Millennium Ecosystem Assessment, 2005; Tockner & Stanford, 2002; Fisher et al., 2009). This framing is widely supported by floodplain ecology literature, which demonstrates that hydrological connectivity and flood pulses underpin ecosystem productivity and service delivery (Junk et al., 1989; Ward, 1989). At the same time, the literature highlights that anthropogenic modification of flood regimes can disrupt ecosystem service flows and amplify risk exposure (Poff et al., 1997; Opperman et al., 2017).

Third, transformative adaptation shifts the focus from incremental responses to systemic change, addressing the root causes of vulnerability and exposure. It highlights the political,

social, and institutional dimensions of adaptation, emphasizing thresholds, power relations, and the need for structural transformation in highly flood-prone environments (Pelling, 2011; Kates et al., 2012; IPCC, 2022). This body of work is grounded in evidence that incremental adaptation may be insufficient under escalating climate risks, particularly where exposure and vulnerability are structurally embedded (Oppenheimer et al., 2014; Eriksen et al., 2015). It also aligns with transition and systems literature that conceptualizes transformation as a response to regime shifts or critical thresholds in coupled systems (Walker et al., 2004; Scheffer et al., 2001).

Lastly, resilience offers a multidimensional lens for understanding system responses to flooding, encompassing absorptive, adaptive, and transformative capacities. While it emphasizes the ability to live with floods, it is also critically examined for potentially obscuring issues of equity and deeper structural change (Folke, 2006; Béné et al., 2012; Cannon & Müller-Mahn, 2010). Resilience thinking is strongly embedded in social–ecological systems literature, which emphasizes learning, adaptation, and transformability under conditions of uncertainty and disturbance (Walker et al., 2004; Folke et al., 2010). However, critical scholarship highlights that resilience discourses can inadvertently normalize vulnerability by focusing on system persistence rather than addressing underlying power structures (Brown, 2014; Davoudi et al., 2012).

The review integrates these frameworks to highlight floodplains as complex, dynamic systems shaped by interactions between hydrological processes, ecosystem functions, and societal responses. Across all four perspectives, a common analytical thread is the importance of feedback, nonlinearity, and cross-scale interactions in shaping flood risk and adaptation

outcomes (Liu et al., 2007; Sivapalan et al., 2012). Together, they underscore the need for approaches that account for trade-offs between ecosystem services and exposure, the political economy of adaptation, and the conditions under which resilience may evolve into transformative change under increasing flood risk (IPCC, 2022; Opperman et al., 2017).

2.2 Methodological review

The second section of the literature review addresses methodological approaches to assess and evaluate flood–human interactions and risk dynamics in wetland floodplain systems. Understanding such interactions—particularly in complex, data-scarce environments such as large tropical wetlands—requires methodological approaches that can simultaneously capture (i) the physical dynamics of flooding, (ii) the spatial distribution and temporal variability of human exposure, and (iii) the empirical realities of hydrological processes in specific case-study regions. There is no single methodological tradition that is sufficient to address these interlinked challenges.

Against this backdrop, this methodological review is structured around three complementary strands: global modelling of population exposure to flood risk (2.2.1), application of satellite remote sensing and Earth observation techniques (2.2.2), and satellite observations in the Sudd (2.2.3). These strands are selected deliberately to reflect three distinct but interdependent scales and epistemologies of analysis.

First, global flood modelling frameworks provide a systematic and scalable approach to quantifying flood hazard and population exposure across large spatial domains. They are indispensable for situating local flood risks within broader climatic and socio-economic trajectories, and for identifying generalizable patterns and uncertainties in flood risk assessment. However, their reliance on generalized assumptions and simplified representations of hydrological processes often limits their applicability in highly heterogeneous wetland systems.

Second, satellite remote sensing and Earth observation techniques offer an observationally grounded methodology capable of capturing spatially explicit flood dynamics and land–water interactions. These methods are particularly critical in regions where in situ data are sparse or unreliable, enabling empirical validation and refinement of model-based approaches. Remote sensing thus serves as a bridge between abstract modelling frameworks and real-world hydrological processes.

Third, the specific application of satellite observations in the Sudd provides a case-based methodological lens through which the limitations and opportunities of both global models and remote sensing approaches can be critically evaluated. The Sudd represents an extreme case of a large, dynamic wetland floodplain characterized by strong hydrological variability, limited ground observations, and complex human–environment interactions. Focusing on this case allows for an assessment of how existing methodologies perform under conditions of high uncertainty and data scarcity, and where methodological innovations are most needed.

These three strands form a coherent methodological framework: global models provide the macro-scale structure of flood risk assessment, remote sensing supplies empirical constraints and spatial detail, and the Sudd case study exposes the practical and conceptual limits of current approaches. Their integration is therefore essential for advancing a robust, multi-scalar understanding of flood risk dynamics in wetland floodplains.

The methodological review therefore presents different approaches for flood modelling and population exposure (2.2.1), describing remote sensing and spatial analysis techniques (2.2.2), and showing how these works have been instrumental in advancing an understanding of flood hazards in the Sudd (2.2.3). The methodological review summarizes the research methodological gaps (2.2.4), describing the approaches taken in this thesis to answer the three main research questions, and ending with a rationale for integrating multiple approaches. This methodological review is thus organized into three key components: global modelling of population exposure to flood risk, application of satellite remote sensing and Earth observation techniques, and satellite observations in the Sudd.

2.2.1 Global modelling of population exposure to flood risk

Advances in global flood modelling frameworks

Modern global flood models (GFMs) integrate hazard, exposure, and vulnerability to support decision-making under uncertainty (Ward et al., 2015; Winsemius et al., 2016). These frameworks are grounded in broader developments in global hydrological modelling and

integrated risk assessment, which emphasize the coupling of physical flood processes with socio-economic exposure patterns (Alfieri et al., 2017; Winsemius et al., 2018). Advances in computational capacity have enabled high-resolution global simulations (~30–90m), improving the representation of floodplain processes alongside enhanced river routing schemes and dynamic floodplain storage (Yamazaki et al., 2011; Nearing et al., 2024). These improvements are consistent with a wider trend toward physically based, high-resolution global hydrodynamic modelling of inundation processes (Hirabayashi et al., 2013; Neal et al., 2015).

Recent intercomparison exercises, such as CMIP6, highlight the sensitivity of projected fluvial flood changes to model structure and forcing (Hirabayashi et al., 2021). Complementary work demonstrates that structural uncertainty in river routing, floodplain representation, and boundary conditions can substantially alter global flood exposure estimates (Sampson et al., 2015; Arnell & Gosling, 2016). Bernhofen et al. (2021) show that constraints on river representation can lead to global exposure estimates differing by more than a factor of two. At the basin scale, Mohamed et al. (2005) demonstrated the hydrological significance of wetlands by simulating scenarios with and without the Sudd, while Marthews et al. (2022) coupled JULES with CaMa-Flood to model global wetland dynamics. Their comparison with GIEMS satellite data showed good large-scale agreement but persistent regional biases linked to uncertainties in hydrological processes and observations. These findings align with broader literature emphasizing the difficulty of accurately representing wetlands and floodplain storage in global-scale hydrological models (Prigent et al., 2020; Paiva et al., 2013).

Emerging research emphasizes the importance of incorporating land-use change and socio-economic scenarios, which remain underrepresented drivers of future flood risk (Shen et al.,

2025). This reflects a growing recognition in global risk modelling that exposure dynamics are as important as hazard projections in shaping future flood risk patterns (Jongman et al., 2012; Winsemius et al., 2016). A key frontier is the integration of machine learning (ML) with physically based models. While purely data-driven approaches offer strong predictive performance, they often lack interpretability (Kratzert et al., 2019). Hybrid "physics-informed" approaches—such as Convolutional Neural Network–Long Short-Term Memory (CNN–LSTM) architectures—combine spatial and temporal modelling capabilities and have shown improved performance for compound flood events (Shen et al., 2025; Nearing et al., 2024). This shift reflects a broader recognition that combining process-based understanding with data-driven methods yields more robust and generalizable models (Reichstein et al., 2019), consistent with hybrid modelling paradigms in Earth system science (Bergen et al., 2019; Willard et al., 2020).

Applications in data-scarce and ungauged basins

In ungauged basins, GFMs increasingly rely on satellite-derived datasets. Precipitation products from missions such as the Global Precipitation Measurement and Tropical Rainfall Measuring Mission provide critical model inputs (Hou et al., 2014; Skofronick-Jackson et al., 2017). The growing use of satellite precipitation in hydrological modelling reflects its demonstrated utility in improving global runoff and flood estimation in data-scarce regions (Beck et al., 2017; Tang et al., 2016). Precipitation is often identified as the most influential variable in ML-based flood prediction (Nikolopoulos et al., 2022), consistent with broader sensitivity analyses in hydrological modelling frameworks (Shu & Ouarda, 2008).

Flood extent products derived from optical and synthetic aperture radar (SAR) imagery are widely used as training data, with U-Net-based models achieving high accuracy in mapping inundation (Li et al., 2021). The use of deep learning for flood detection from remote sensing imagery is increasingly established in Earth observation literature (DeLancey et al., 2019; Tanim & Aksoy, 2021). Global datasets such as the Global Surface Water Explorer further support large-scale model calibration and validation (Pekel et al., 2016). These datasets are widely recognized as key benchmarks for long-term surface water dynamics and floodplain monitoring (Foufoula-Georgiou et al., 2019).

To improve transferability, ML frameworks increasingly incorporate static catchment attributes—such as topography, soils, and land use—which help explain spatial variability in hydrological response (Addor et al., 2017; Nearing et al., 2021). This approach is consistent with the development of "catchment signature" and regionalization methods in hydrology, which aim to transfer learning across ungauged basins (Sawicz et al., 2011; McMillan et al., 2016). These approaches enable regionalization, allowing models trained in data-rich areas to be applied in ungauged basins.

In summary, global flood modelling is evolving toward integrated, probabilistic, and data-rich frameworks. However, key challenges remain. Uncertainty propagation across the modelling chain is still insufficiently quantified, particularly in hybrid models. This challenge is widely recognized in the flood risk and Earth system modelling literature, where cascading uncertainties from climate forcing, hydrological processes, and exposure layers remain difficult to fully characterize (Sampson et al., 2015; Arnell & Gosling, 2016). Validation is constrained by limited observations, especially in data-scarce regions. Human–water interactions (e.g.,

reservoirs, flood defenses, and land-use change) remain poorly represented, despite their known importance in shaping flood regimes globally (Di Baldassarre et al., 2010; Zeng et al., 2017). Trade-offs between spatial resolution and computational cost limit ensemble-based uncertainty analysis, a challenge widely discussed in high-resolution hydrodynamic modelling studies (Neal et al., 2015). Lastly, socio-economic dynamics—critical for determining real-world risk—are often underrepresented, even though exposure change is a dominant driver of future flood risk globally (Jongman et al., 2012; Winsemius et al., 2018). Addressing these issues is essential for improving the reliability and policy relevance of GFMs.

2.2.2 Application of satellite remote sensing/Earth Observations

The use of satellite remote sensing, combined with Geographic Information Systems (GIS), has expanded significantly over the past two decades as high-resolution imagery has become increasingly available (Adegoke et al., 2010; Passalacqua et al., 2013; Paszkowski, 2022). This expansion reflects broader developments in Earth observation science, particularly the increasing availability of multi-sensor, multi-temporal datasets for monitoring environmental change and human–environment interactions at scale (Pettorelli et al., 2014; Wulder et al., 2012). Although satellite records are temporally limited to the post-1970s era, their broad spatial coverage enables analysis of human–environment interactions at scales not achievable through in-situ observations alone (Townshend et al., 2012; Woodcock et al., 2008).

Remote sensing has proven particularly valuable in wetland and floodplain environments. Sosnowski et al. (2016), for example, used MODIS thermal infrared and NDVI data to map land cover changes in the Sudd. Similarly, Petersen et al. (2007) analyzed Landsat imagery to quantify long-term changes in the Sudd's channel and lagoon systems, while Rebelo et al. (2012) used multi-sensor datasets to characterize flood pulsing over a 12-month period, estimating a total flooded area of 41,334 km², including 9,176 km² of permanent wetland. These applications are consistent with broader wetland remote sensing literature, which demonstrates the effectiveness of optical and radar sensors in capturing inundation dynamics and vegetation structure in large floodplain systems (Adam et al., 2010; Prigent et al., 2020).

More generally, satellite-based flood mapping has become a core component of hydrological and hazard research, particularly through the use of optical imagery (e.g., Landsat, MODIS) and Synthetic Aperture Radar (SAR), which allows penetration through cloud cover and supports near-real-time inundation detection (Giustarini et al., 2013; Hostache et al., 2018). These approaches are especially important in regions such as the Sudd, where in-situ data are sparse or incomplete due to logistical and political constraints (Petersen et al., 2008a; Rebelo et al., 2012; Tate, Sene, & Sutcliffe, 2001). Such data scarcity is widely recognized in global hydrology and remote sensing literature as a major constraint on model calibration and validation in tropical floodplain environments (Bjerklie et al., 2011; Smith, 1997).

As a result, remote sensing provides a critical alternative for analyzing hydrological processes, land cover dynamics, and population exposure. Increasingly, satellite-derived datasets are also being integrated with population distribution products (e.g., WorldPop, GHSL) to estimate exposure to flood hazards at high spatial resolution (Tatem, 2017; Freire et al., 2016). More

broadly, GIS-based analyses have demonstrated strong utility in mapping hazard exposure and supporting the study of human–nature systems (Paszkowski, 2022). This integration of spatial data science and Earth observation is widely recognized as a key pillar in contemporary environmental risk analysis (Goodchild, 2007; Longley et al., 2015).

In summary, satellite remote sensing and GIS are now indispensable tools for analyzing flood hazards and wetland dynamics, particularly in data-scarce regions. While limitations in temporal resolution and historical coverage remain, multi-temporal and multi-sensor datasets enable large-scale, long-term assessments that would otherwise be unattainable. The literature highlights the importance of integrating these data with hydrodynamic and land surface models to improve predictive capability and strengthen understanding of flood risk under climate change (Foufoula-Georgiou et al., 2019; Wood et al., 2011**)**.

2.2.3 Satellite observations in the Sudd

In the data-scarce environment of South Sudan, satellite observations are central to reconstructing the hydrology of the Sudd. Limited ground-based monitoring—largely due to decades of conflict—has necessitated reliance on remotely sensed data, including MODIS, Landsat, and satellite altimetry (Di Vittorio and Georgakakos, 2021). This reliance reflects a broader pattern in global hydrology, where conflict-affected and remote basins are increasingly studied through Earth observation platforms due to the absence of sustained in-situ hydrometric networks (Smith, 1997; Bjerklie et al., 2011). While historical in-situ flow records exist for the Nile Basin (1905–1984), contemporary analyses depend heavily on satellite-derived

observations, particularly for characterizing wetland dynamics under changing climatic and hydrological conditions (Sutcliffe & Parks, 1999; Mohamed et al., 2005).

MODIS provides detailed information on surface water dynamics, while GRACE captures total water storage changes, offering complementary perspectives on hydrological processes. The combined use of optical and gravimetric satellite products has become a standard approach for assessing large-scale hydrological variability in data-limited regions (Tapley et al., 2004; Rodell et al., 2007). However, a recurring theme in literature is the uncertainty associated with these approaches, as models often overestimate flood extent or fail to capture hydrological connectivity accurately. Such limitations are widely documented in wetland remote sensing studies, particularly where mixed land–water pixels and seasonal inundation dynamics complicate classification (Prigent et al., 2020; Adam et al., 2010).

Remote sensing and GIS have also been applied to assess flood exposure in South Sudan, enabling the identification of settlements at risk (Yagoub & Mahmoud, 2022). This aligns with broader applications of geospatial analysis in humanitarian and disaster risk contexts, where satellite-derived settlement and flood maps are used to support exposure estimation in fragile settings (Tatem et al., 2012; Smith & Finch, 2016). Studies such as Lukwasa et al. (2022) further highlight the importance of large-scale climate variability in shaping hydrological processes, consistent with established evidence linking Nile Basin hydrology to ENSO and other climate oscillations (Seleshi & Zanke, 2004; Conway, 2005). At the same time, improved representation of wetlands in land surface and hydrodynamic models remains a key research priority (Zhang et al., 2016; Marthews et al., 2022; Christopher et al., 2017), reflecting persistent challenges in

simulating wetland storage, exchange fluxes, and floodplain connectivity at large scales (Paiva et al., 2013; Prigent et al., 2020).

Modelling studies underscore these challenges. Marthews et al. (2020), using the JULES–CaMa-Flood framework, demonstrated that overbank flooding is a critical driver of Sudd inundation, while also highlighting significant uncertainties in precipitation, runoff, and floodplain processes. These findings are consistent with broader hydrodynamic modelling literature emphasizing sensitivity to rainfall forcing and floodplain parameterization in large wetland systems (Yamazaki et al., 2011; Neal et al., 2015). Similarly, Di Vittorio and Georgakakos (2021) improved model performance through iterative refinements, generating new insights into Sudd hydrology. Such calibration-driven improvements reflect a wider trend in hydrological modelling, where iterative assimilation of satellite observations is used to constrain poorly observed systems (Alsdorf et al., 2007; Pavelsky & Smith, 2008).

In conclusion, satellite observations are indispensable for understanding the Sudd's hydrology in the absence of reliable ground data. While they have significantly advanced knowledge of surface water dynamics and total water storage, substantial uncertainties remain in modelling flood extent and connectivity. These uncertainties are widely recognized in global wetland and floodplain literature, particularly where seasonal inundation and vegetation dynamics introduce classification and scaling challenges (Prigent et al., 2020; Adam et al., 2010). Moreover, existing studies largely neglect the human dimension, particularly population exposure and lived experiences of flooding. This gap reflects a broader limitation in hydrological remote sensing research, which has historically prioritized biophysical processes over socio-economic vulnerability and exposure dynamics (Di Baldassarre et al., 2015; IPCC, 2022). Addressing

these gaps is essential for developing more integrated and policy-relevant assessments of flood risk in the Sudd region.

2.2.4 Summary of methodological reviews

The methodological literature review in this section demonstrates that the assessment of flood risk in wetland floodplains requires the integration of modelling, observational, and case-specific approaches. Global flood models have advanced significantly in their ability to simulate flood hazard and estimate population exposure at scale, incorporating probabilistic frameworks, higher spatial resolution, and emerging machine learning techniques. However, they remain constrained by uncertainties in input data, limited representation of human–water interactions, and challenges in validation, particularly in data-scarce regions (Ward et al., 2015; Winsemius et al., 2016; Alfieri et al., 2017). These limitations are widely recognized in global flood risk modelling literature, especially regarding structural uncertainty and exposure representation (Sampson et al., 2015; Arnell & Gosling, 2016). These challenges are also consistent with broader Earth system modelling limitations related to cascading uncertainty across coupled hazard–exposure systems (Beven, 2016; Refsgaard et al., 2013).

Satellite remote sensing and Earth observation techniques address many of these limitations by providing spatially explicit, empirically grounded data on flood extent, hydrological dynamics, and land cover change. These approaches are especially valuable in inaccessible environments, enabling long-term and large-scale analyses that would otherwise be infeasible (Pettorelli et al., 2014; Wulder et al., 2012). Their role is widely recognized as fundamental to modern hydrology

and environmental monitoring systems (Pekel et al., 2016; Wood et al., 2011). Nonetheless, they are also subject to constraints in temporal resolution, sensor limitations, and difficulties in capturing subsurface or hydrological connectivity processes (Adam et al., 2010; Prigent et al., 2020). In addition, uncertainties in flood detection from optical and radar data remain a persistent challenge, particularly in densely vegetated or seasonally inundated wetlands (Giustarini et al., 2013; Hostache et al., 2018). These limitations are well documented in remote sensing literature dealing with mixed-pixel classification and floodplain inundation dynamics (Townshend et al., 2012; Brakenridge et al., 2007).

The Sudd case study highlights both the necessity and the limitations of these methodologies. Satellite-based observations have become indispensable for reconstructing the hydrology of the region, yet significant uncertainties persist in modelling flood extent and dynamics. These uncertainties are consistent with broader evidence from global wetland and floodplain systems, where complex hydrological connectivity and data scarcity limit model precision (Paiva et al., 2013; Prigent et al., 2020). Similar challenges are reported in large tropical wetland systems where seasonal inundation and vegetation dynamics complicate remote sensing retrievals (Hess et al., 2003; Papa et al., 2010). Moreover, a critical gap remains in linking hydrological processes to human exposure and vulnerability, reflecting a wider disconnect between biophysical modelling and socio-economic risk assessment in flood research (Di Baldassarre et al., 2015; IPCC, 2022). This gap has been widely emphasized in disaster risk science, particularly in relation to exposure mapping and the integration of socio-economic data layers into hazard models (Jongman et al., 2012; Tatem et al., 2017).

Finally, the literature points toward the need for a multi-method, integrative approach that combines global modelling frameworks, satellite observations, and case-specific analysis. Such integration is essential for improving the robustness, realism, and policy relevance of flood risk assessments in complex wetland systems. This direction aligns with broader calls in Earth system science and disaster risk research for coupled human–natural system approaches that explicitly integrate hazard, exposure, and vulnerability across scales (Liu et al., 2007; Winsemius et al., 2018). It also reflects an emerging consensus that hybrid methodologies combining process-based models, remote sensing, and socio-economic data provide the most promising pathway for improving predictive and explanatory power in flood risk science (Reichstein et al., 2019; McMillan et al., 2016).

CHAPTER 3

3 STUDY AREA

3.1 East African climate

The climate of East Africa is characterized by marked spatial and temporal variability, shaped by the interaction of large-scale atmospheric circulation systems, regional topography, and ocean–atmosphere processes. Understanding these dynamics is critical for analyzing patterns of environmental risk, particularly in relation to flooding, drought, and human exposure. This section synthesizes the key strands of the literature on East African climate, with particular attention to rainfall seasonality, drivers of variability, long-term trends, and ongoing debates surrounding climate change projections.

3.1.1 Seasonal structure of East African climate

The literature consistently identifies large-scale ocean–atmosphere interactions as the dominant drivers of interannual climate variability in East Africa. In particular, the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) play central roles. ENSO influences

rainfall through shifts in the Walker circulation, with El Niño events typically associated with enhanced rainfall during the short rains season and La Niña events linked to drought conditions (Ogallo, 1988; Reason et al., 2000). However, ENSO alone does not fully explain observed variability. The IOD, characterized by zonal sea surface temperature gradients in the Indian Ocean, has emerged as a critical complementary driver, particularly for OND rainfall (Saji et al., 1999).

Importantly, recent studies emphasize the interaction between ENSO and the IOD, rather than their independent effects. Positive IOD events, especially when co-occurring with El Niño, can amplify rainfall extremes, contributing to flood events across East Africa (Wainwright et al., 2023). The influence of these oceanic modes occurs through changes in moisture transport, convection intensity, and large-scale circulation patterns that regulate seasonal rainfall anomalies across the region (Ummenhofer et al., 2011). This coupling underscores the need to consider climate variability within a multi-driver framework.

Intraseasonal and regional processes

While teleconnections operate at interannual scales, intraseasonal variability is influenced by phenomena such as the Madden–Julian Oscillation (MJO), tropical cyclones, and regional monsoonal systems (Finney et al., 2020). These processes affect rainfall onset, duration, and intensity, often determining the distribution of rainfall within a season. The MJO has been shown to influence extreme rainfall events in East Africa by modulating atmospheric moisture

convergence and convective activity at weekly to monthly timescales (Pohl and Camberlin, 2006).

Land–atmosphere feedback also play a role, particularly through soil moisture dynamics and vegetation–climate interactions. This feedback can either amplify or dampen rainfall anomalies, though their representation in climate models remains limited (Nicholson, 2019). Such feedback mechanisms are particularly important in wetland and floodplain environments, where hydrological storage and surface processes influence local climate–water interactions (Sene, 2010). Overall, the literature highlights the multi-scalar nature of East African climate variability, where global teleconnections interact with regional and local processes in complex and often nonlinear ways.

3.1.2 Drivers of climate variability

Ocean–atmosphere interactions

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3.1.3 The East African climate paradox

One of the most significant debates in the regional climate literature concerns the "East African climate paradox." Climate model projections generally indicate that East Africa will experience increasing rainfall under global warming, largely associated with enhanced atmospheric moisture availability and intensification of the hydrological cycle under warmer conditions (Held and Soden, 2006; IPCC, 2021). However, observational records from the late twentieth century indicate a decline in the March–May (MAM) "long rains" across much of the region, particularly over parts of Kenya, Tanzania, and Somalia, creating an apparent contradiction between observed historical trends and model-projected future changes (Mölg and Pickler, 2022). This discrepancy has prompted extensive investigation into the mechanisms controlling East African rainfall variability. Proposed explanations include changes in Indian Ocean sea surface temperature gradients, altered Walker circulation dynamics, aerosol forcing, and

limitations in climate models' representation of regional ocean–atmosphere interactions and convection processes (Wainwright et al., 2023). Several studies argue that the decline in long rains may be linked to warming patterns in the western Indian Ocean, which modify moisture transport and atmospheric circulation pathways affecting East African rainfall (Funk et al., 2008; Lyon and DeWitt, 2012).

Recent research suggests that the observed reduction in long rains may not represent a permanent long-term drying trend but rather a period of pronounced decadal variability within a highly complex climate system. Evidence from more recent observations indicates partial recovery of long-rainfall conditions in parts of East Africa during the early twenty-first century, challenging interpretations based solely on late twentieth-century trends (Palmer et al., 2023). Such variability highlights the difficulty of separating forced climate change signals from natural climate oscillations operating across interannual and decadal timescales (Hoell and Funk, 2014; Nicholson, 2017).

Nonetheless, substantial uncertainty remains regarding the future trajectory of the long rains. While many climate models project increased annual rainfall under future warming scenarios, there remains considerable disagreement concerning the magnitude, timing, and seasonal distribution of rainfall changes, particularly for the MAM season (Rowell et al., 2015; Tierney et al., 2015). These uncertainties arise from differences among climate models in simulating tropical convection, Indian Ocean dynamics, land–atmosphere feedback, and regional circulation patterns (Otieno and Anyah, 2013; Rowell et al., 2015). As a result, future changes in East African rainfall cannot be interpreted simply as a linear continuation of historical trends. This unresolved tension between observed drying trends and projected future wetting remains

a major challenge for climate impact assessment and adaptation planning. For flood-prone environments such as the Sudd wetland, uncertainty in future rainfall regimes has important implications because both increased precipitation and altered seasonal variability can influence river discharge, wetland inundation dynamics, ecosystem productivity, and human exposure to flood risk (Conway, 2005; Di Baldassarre et al., 2013). Understanding this climate uncertainty is therefore essential for interpreting future flood trajectories and designing adaptation strategies that remain robust under changing hydrological conditions.

3.1.4 Observed trends and climate change

Rainfall trends and extremes

Empirical analyses indicate divergent trends between the two rainfall seasons. While the long rains experienced a decline between the 1980s and early 2000s, the short rains have shown a tendency towards intensification, with increased frequency of extreme rainfall events (Palmer et al., 2023). These contrasting seasonal trends demonstrate that climate change impacts in East Africa are not expressed uniformly across seasons, but rather through shifts in rainfall timing, intensity, and variability (Rowell et al., 2015). This shift has important implications for flood risk, as short rains are more closely associated with extreme precipitation events linked to ENSO and IOD variability. Notable examples include the 1997–1998 El Niño floods and more recent extreme rainfall events across the region (Funk et al., 2015). The 1997–1998 event was among the strongest recorded climate anomalies of the twentieth century in East Africa and produced widespread flooding due to enhanced moisture transport from the Indian Ocean

(Webster et al., 1999). At the same time, drought frequency has increased in parts of the Horn of Africa, reflecting heightened climate variability rather than uniform drying. This coexistence of increasing flood and drought risks has been attributed to greater climate variability and changes in atmospheric circulation patterns rather than a simple regional shift toward wetter or drier conditions (Nicholson, 2017).

Temperature and hydrological change

Rising temperatures across East Africa have intensified evapotranspiration, contributing to increased water stress even in areas where rainfall has not declined significantly (Taylor et al., 2013). This has implications for both agricultural productivity and hydrological systems. Observed warming trends across East Africa are consistent with broader global temperature increases and have altered the regional water balance by increasing atmospheric evaporative demand (IPCC, 2021).

Recent studies highlight a shift towards greater reliance on extreme rainfall events for groundwater recharge, suggesting a transformation in hydrological regimes under climate change (Taylor et al., 2013). Changes in rainfall intensity can modify runoff generation processes, increasing the proportion of precipitation lost as surface runoff rather than contributing to gradual soil moisture and groundwater replenishment (Tramblay et al., 2020). Such changes may exacerbate both flood and drought risks, depending on local conditions. These hydrological changes are particularly important in river–wetland systems, where altered

inflow patterns can affect inundation extent, seasonal storage, and ecosystem functioning (Junk et al., 2013).

3.1.5 Summary and research gaps

The literature on East African climate converges on several key insights. First, the region's climate is inherently variable and strongly influenced by ocean–atmosphere teleconnections. Second, rainfall seasonality is asymmetric, with distinct drivers and trends for the long and short rains. Third, uncertainty remains a defining feature of both observational trends and future projections. This uncertainty is partly due to limitations in observational records, sparse long-term climate monitoring networks, and challenges in representing tropical convection in climate models (Hawkins and Sutton, 2012).

Several research gaps are particularly relevant for this thesis. These include the need to better understand the mechanisms underlying the variability of the long rains, the role of regional feedback such as land use change, and the implications of climate variability for human exposure in flood-prone environments.

Addressing these gaps is essential for advancing both scientific understanding and practical adaptation strategies. The high variability of East African climate has profound implications for socioeconomic systems, particularly in contexts characterized by dependence on rain-fed agriculture and limited adaptive capacity. Climate-sensitive livelihoods in East Africa remain strongly dependent on seasonal rainfall reliability, making communities vulnerable to both gradual climatic shifts and short-duration extremes (Thornton et al., 2014). Rainfall variability

is closely linked to food insecurity, livelihood instability, and migration dynamics (Conway et al., 2017). Climate-related livelihood disruption can influence mobility decisions by affecting agricultural productivity, pastoral resources, and access to water, although migration outcomes are also shaped by social, economic, and political factors (McLeman, 2017).

Flooding and drought represent two sides of the same climatic system, with both hazards often occurring within short temporal intervals. This dual exposure complicates adaptation strategies and underscores the importance of understanding climate variability in relation to human vulnerability and resilience. Such compound climate risks are increasingly recognized as a major challenge because adaptation strategies designed for a single hazard may be insufficient under conditions of interacting extremes (Zscheischler et al., 2018).

Ecosystems are similarly affected, with rainfall variability influencing vegetation dynamics, biodiversity, and ecosystem services. Changes in rainfall timing and intensity can alter ecosystem productivity, species distributions, and the functioning of African wetlands and floodplain systems (Dudgeon et al., 2006). Wetland systems, floodplains, and savanna landscapes are particularly sensitive to changes in rainfall timing and intensity. Floodplain wetlands depend on seasonal hydrological connectivity, meaning that changes in river discharge and inundation patterns can affect nutrient cycling, fisheries, grazing resources, and ecosystem services (Junk et al., 2013).

3.2 South Sudan national setting: Geography, climate, and the environment

South Sudan is a landlocked country, located in East and Central Africa, and encompasses an area of 644,329 sq km. South Sudan shares geographic boundaries with several countries, including Kenya 317 km, Uganda 475 km, Democratic Republic of the Congo 714 km, Central African Republic 1055 km, Ethiopia 1299 km, and Sudan 2158 km. South Sudan's territory is almost all part of the Nile River system. The spatial position of South Sudan within the wider Nile Basin system was assessed by comparing national areas with the portion of each country falling within the Nile Basin boundary (Table 2). Country boundary data were intersected with the Nile Basin boundary to estimate the area of each country within the basin. The percentage contribution of each country to the total Nile Basin area and the proportion of each country located within the basin were subsequently calculated. Therefore, the values presented in Table 2 represent author-derived calculations based on spatial analysis rather than directly reported statistics. Approximately 97.5 percent of South Sudan's land area is within the Nile Basin (Table 2), as the country is dominated by the White Nile and its tributaries (Salman M.A. Salman, 2011). About 20 percent of the Nile Basin lies within South Sudan and about 9 to 14 percent of which is covered by the Sudd Wetland, making it regionally significant and an important part of the Nile Basin water network (NBI, 2020).

Table 2: South Sudan within the Nile Basin System. Source: Author's compilation based on country boundary and Nile Basin spatial datasets. Country areas and Nile Basin overlap areas

were derived through GIS intersection analysis; percentage values were calculated by the author.

Country	Country Area (KMSQ)	Area within the Nile Basin (KMSQ)	% of the Total Nile Basin Area	% of the Country in the Nile Basin
Burundi	27,835	13,260	0.4	47.6
DR Congo	2,345,410	22,143	0.7	0.9
Egypt	1,001,450	326,751	10.5	32.6
Eritrea	121,320	24,921	0.8	20.5
Ethiopia	1,127,127	365,117	11.7	32.4
Kenya	582,650	46,229	1.5	7.9
Rwanda	26,340	19,876	0.7	75.5
Sudan	1,886,068	1,396,230	44	75
South Sudan	644,329	620,626	20	97.5
Tanzania	945,090	84,200	2.7	8.9

Uganda	236,040	231,366	7.4	98
Total	8,919,072	3,112,369	100.0	34.9

South Sudan experiences a tropical climate, with average temperatures above 25°C, and highs exceeding 35°C, particularly during the dry season (January to April). The upstream part of the Bahr el Jebel/White Nile lies in the tropical wet and dry zone with a winter dry season and two wet seasons, whereas the downstream part is influenced by the subtropical dry, semi-arid climate with only one wet season occurring between May and October and its counterpart dry season between November and April (NBI Monograph, 2020; Sutcliffe and Parks, 1999). The lowland areas of Eastern Equatoria, Jonglei, the Upper Nile and Bahr el Ghazal receive annual rainfall between 700 and 1,300 mm. The heaviest rainfall occurs in the southern upland areas and lessens northward. Western Equatoria and the highland parts of Eastern Equatoria receive between 1,200 and 2,200 mm of rainfall annually. The monthly rainfall variations are controlled by the movement of the intertropical convergence zone and can be highly seasonal and variable from year to year (Wilusz et al., 2017).

The White Nile River (Bahr el Jebel) runs through the country from south to north, where It Is joined by its major tributaries, the Bahr el-Ghazal to the west, and the Sobat River system to the east (Figure 4). The center of the country is dominated by a landmark geographic feature of

the country, the Sudd wetlands (Maystadt et al., 2014; UNEP, 2018; Bavumiragira et al., 2019; AfDB, 2013).

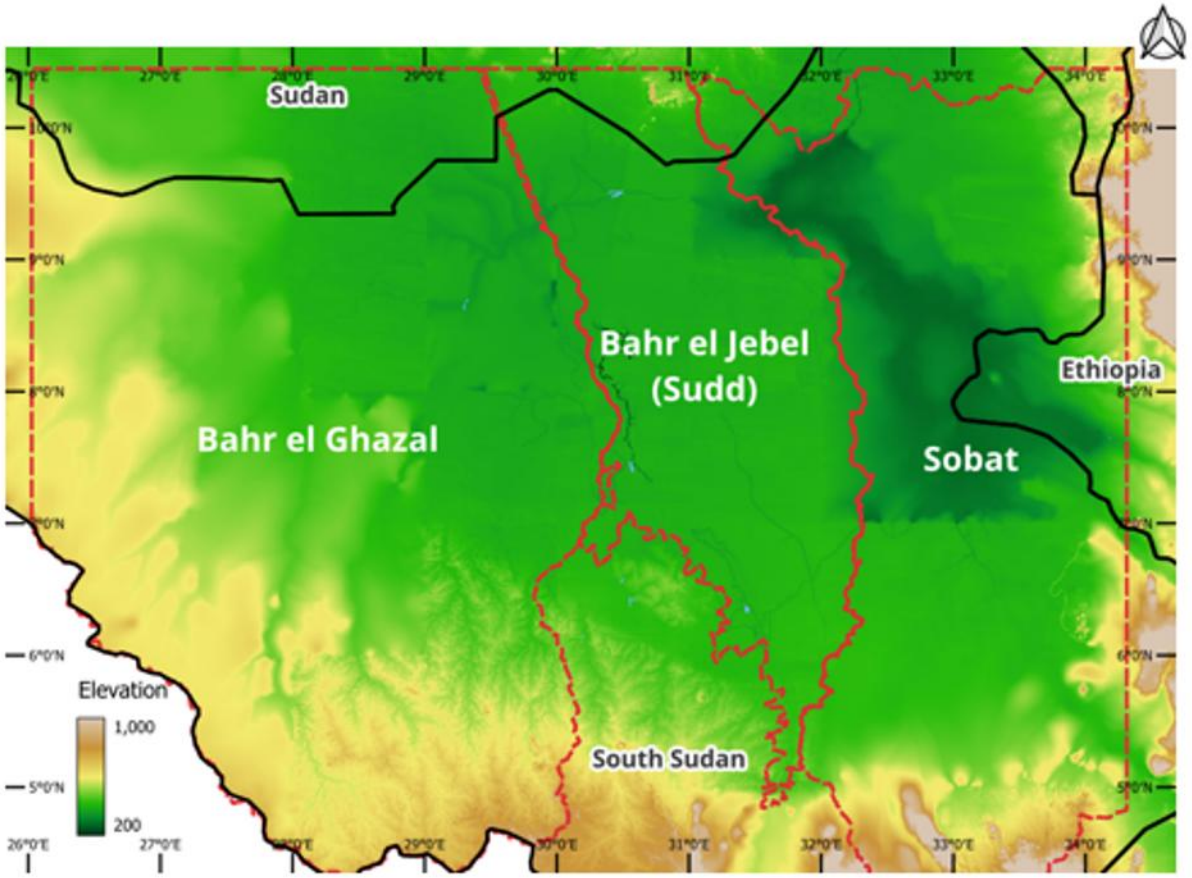


Figure 4: Study area: Location of the Sudd wetland in central South Sudan. Inflow to the Sudd comes from the Bahr el Jebel, which flows from Juba to Malakal (source: Rebelo et al., 2012).

The Sudd, a term derived from the Arabic word “sadd,” meaning barrier, is the largest tropical wetland in Africa, and includes savannah and extensive floodplains around the Sudd’s permanent wetlands and swamps. The Sudd is situated in South Sudan in the lower reaches of Bahr el Jebel/White Nile at an elevation of 380-450m above mean sea level. The Sudd wetland has a long environmental and human history shaped by the Nile’s hydrology. Across history, the Sudd evolved from a naturally formed floodplain wetland into a major hydrological feature of the Nile Basin, a barrier to exploration and navigation for millennia, and a cultural landscape

sustaining indigenous livelihoods (Mooreheads, 1960). During early formation (geologic–hydrologic origins), the Sudd formed naturally as part of the White Nile (Bahr al-Jabal/Jebel) system, where very flat topography and impermeable clay soils caused water to spread into vast, shallow floodplains (UNESCO, 2017).

Seasonal environmental variability has long shaped human settlement and livelihoods in the Sudd region. Nilotic peoples, including the Dinka, Nuer, and Shilluk, have historically adapted to these conditions through pastoralism, fishing, and mobile settlement systems aligned with seasonal cycles (UNESCO, 2017). Classical anthropological studies (e.g., Evans-Pritchard, 1940; Seligman and Seligman, 1932) identify pastoralism as the organizing principle of these societies, with mobility serving as a key strategy for managing environmental uncertainty and resource access.

The Sudd was designated a Ramsar Site of International Importance on June 5, 2006, covering approximately 57,000 square kilometers (Ramsar Convention, 2015). This designation underscores its global ecological and socio-economic significance. Historical studies throughout the twentieth century (e.g., Hurst and Phillips, 1931; Butcher, 1938; Jonglei Investigation Team, 1954) contributed to early understandings of land classification, soil systems, and settlement environments in the region. These studies identified diverse land types, including permanent swamps, seasonally inundated grasslands (toich), intermediate lands, and relatively elevated highlands, which together shape patterns of human activity and land use (De Mabior, 1981).

Soils in the Sudd region are predominantly vertisols—heavy clay “black cotton soils” common across African floodplains (IUSS WRB, 2006). These soils are highly fertile and support

agricultural and grazing activities, but their physical properties present significant constraints. Seasonal expansion and contraction can damage infrastructure, while low permeability contributes to waterlogging, limiting cultivation and settlement stability. These soil characteristics play a crucial role in shaping land use decisions, mobility patterns, and livelihood strategies.

Vegetation in the Sudd reflects a mosaic of ecological zones, including permanent swamp vegetation, seasonally inundated grasslands, and floodplain woodlands. Grass species, both annual and perennial, are particularly important for livestock production and thus underpin pastoral livelihoods. Tree cover is generally sparse and largely confined to higher ground due to environmental constraints and human use. The distribution and seasonal availability of vegetation strongly influence livestock movement, grazing patterns, and broader socio-economic organization in the region (De Mabior, 1981). These socio-ecological patterns and livelihood strategies are fundamentally shaped by the Sudd's underlying hydrological dynamics, which are examined in detail in the following section.

3.3 Hydrology of the Sudd

The Nile is one of the world's longest rivers. While the Nile drainage area is comparable to those of the Amazon, Congo, and Mississippi River systems (Table 3), its annual discharge is considerably lower, only slightly exceeding that of the Rhine River. This difference reflects the combined effects of climatic conditions, upstream water losses, high evaporation rates, and the attenuating influence of the Sudd wetland. The comparatively low runoff efficiency of the Nile basin has long been attributed to extensive evaporative losses, large wetland storage areas, and

the seasonal retention of floodwaters within the White Nile system (Sutcliffe and Parks, 1999). The comparatively low discharge intensity of the Nile relative to other major rivers highlights the important hydrological role of the Sudd, where extensive seasonal inundation increases water storage, slows downstream flow, and contributes to substantial evaporative losses. The Nile is the longest river in the world. While the Nile drainage area is comparable to those of Amazon, Congo, and Mississippi River systems (Table 3), its annual discharge is considerably lower, only slightly exceeding that of the Rhine River. This difference reflects the combined effects of climatic conditions, upstream water losses, high evaporation rates, and the attenuating influence of the Sudd wetland. The comparatively low discharge intensity of the Nile relative to other major rivers highlights the important hydrological role of the Sudd, where extensive seasonal inundation increases water storage, slows downstream flow, and contributes to substantial evaporative losses.

Table 3: Characteristics of major rivers of the world and comparison of hydrological attributes with the Nile River. Source: Author's compilation based on published river basin datasets and hydrological literature. River length, drainage area, and annual discharge values were compiled from existing datasets; discharge per unit area was calculated by the author as the ratio of mean annual discharge to drainage area.

River	Length (KM)	Drainage Area 1000 KMSQ	Annual Discharge BCM	Discharge/unit area 1000 CM/SQKM
Nile	6,850	3,110	84	28
Amazon	6700	7, 050	5518	728
Congo	4,700	3,820	1248	326

Mekong	4,200	795	470	590
Niger	4,100	2,274	177	78
Mississippi	970	3,270	562	170
Danube	2,900	816	206	252
Rhine	1,320	224	70	312
Zambezi	2,700	1,200	223	185

Note: Length and drainage area estimates are based on reported river basin characteristics from global hydrological datasets. Annual discharge values represent long-term mean annual flow estimates. The discharge per unit area column was calculated by the author using annual discharge divided by drainage area.

The Sudd wetland is a central hydrological feature of the Nile Basin, often described as its "lung" due to its capacity to regulate water flows, regional climatology, and biogeochemical cycles. Large tropical wetlands such as the Sudd influence regional hydrology by regulating water storage, modifying surface–atmosphere exchanges, and controlling downstream discharge variability (Junk et al., 2013). Its hydrology is governed by a dynamic interaction between upstream inflows, local precipitation, floodplain storage, and evapotranspiration. Rainfall and river discharge recharge the wetlands, floodplains, and groundwater systems, while high evapotranspiration rates return substantial volumes of water to the atmosphere. Through this cyclical process, the Sudd exerts a strong influence on downstream flow regimes and regional climate feedback. The high evaporative losses of the Sudd are a defining feature of the White Nile system, with evaporation accounting for a substantial proportion of incoming water before downstream transmission (Sutcliffe and Parks, 1999).

Beyond its hydrological role, the Sudd provides critical ecosystem services. These include sediment retention, water purification, and carbon sequestration, alongside flood regulation and biodiversity support. Wetlands globally are recognized as critical regulators of hydrological processes, providing flood attenuation, nutrient cycling, carbon storage, and habitat functions (Mitsch and Gosselink, 2015). The wetland sustains extensive fisheries, grazing systems, and wildlife habitats, including one of the largest terrestrial mammal migrations. The ecological productivity of floodplain wetlands is closely linked to seasonal flooding, which drives nutrient exchange and supports fisheries, grazing resources, and biodiversity (Junk et al., 2013). It also underpins agro-pastoral livelihoods and holds significant cultural and socio-economic value, functioning as both an environmental asset and a foundation for local and national economies (NBI/Tadesse et al., 2020; MoEF, 2022).

The hydrology of the Sudd is characterized by pronounced spatial and temporal variability. Flooding patterns are highly heterogeneous: while some experience persistent inundation, others may simultaneously face relative water scarcity. This uneven distribution reflects the region's extremely low-relief topography, which amplifies small changes in water levels into extensive lateral flooding. The very low gradient of the Sudd plain allows relatively small variations in river stage to generate large changes in inundated area, making flood extent highly sensitive to discharge fluctuations (Mohamed et al., 2005).

Riverine floods—caused by the overtopping of riverbanks from the Bahr el Jebel and associated tributaries—are a dominant hydrological feature, interacting with local rainfall and floodplain storage processes. Foundational hydrological and seasonal flood studies on the Sudd, including Petersen and Fohrer (2010), Rebelo et al. (2012), and Johnson (1992), establish the importance

of the annual flood pulse system, which is central to both the region's ecology and local livelihoods. These studies map inundation extent and highlight patterns of seasonal variability. Flood pulse dynamics are fundamental to floodplain ecosystems because the timing, duration, and magnitude of inundation regulate ecological productivity and human resource availability (Junk et al., 1989).

Building on this foundation, Galla et al. (2025) examine multi-decadal flood dynamics, identifying increasing flood risk and linking these trends to broader climate change and hydro-climatic shifts. The "Spade-like Shape" of South Sudan, with a depression in the center of the country, is an accumulation conveyor for flood waters, making the Sudd a key part of the Nile River system that maintains steady flow all year round. The Sudd's position within the Bahr el Jebel system enables it to function as a major hydraulic buffer, delaying flood transmission and sustaining downstream flow during dry periods (Sutcliffe and Parks, 1999).

Sutcliffe and Parks (1999) examine changes to the Nile's regime, including the significant increase in outflows from Lake Victoria and other lakes after 1961. Results show the relationship between hydrology and vegetation affects the economy of the wetlands of the White Nile basin, and this relation is discussed. The Sudd wetland is about 300 m above mean sea level and is the largest freshwater wetland in the Nile basin (Sutcliffe et al., 2016; Tootchi et al., 2019). Satellite-based assessments have confirmed that the Sudd represents one of the largest inland wetlands in Africa, although its seasonal extent varies substantially depending on hydrological conditions (Tootchi et al., 2019).

Some previous works have studied complex and seasonal behavior of the Sudd, including flood severity (World Bank, 2011; Mohamed et al., 2005; Sosnowski et al., 2016; Nile Basin Initiative

(NBI), 2020; Gowdy and Lang, 2016; Lambert, 2009; UNEP, 1997). Sosnowski et al. (2016) describe that variations in upstream sub-basin precipitation alter the extent of wetland cover classes. Remote sensing studies have demonstrated that changes in upstream rainfall and river discharge produce measurable changes in inundation extent and wetland vegetation patterns across the Sudd landscape (Sosnowski et al., 2016).

3.4 Sudd regional hydro-climatic role in the Nile system

The Sudd wetland has been consistently identified as a pivotal component of the Nile Basin's hydro-climatic system, functioning as both a hydrological regulator of the White Nile and a driver of regional atmospheric processes. Within broader analyses of Nile Basin climate variability, the Sudd is conceptualized not merely as a passive storage system, but as an active interface between land–atmosphere interactions and fluvial dynamics (Whittington et al., 2005; Skofronick-Jackson et al., 2017). Large wetlands such as the Sudd influence regional hydroclimate by modifying surface energy exchanges, evapotranspiration fluxes, atmospheric humidity, and downstream water availability (Sene, 2010; Mitsch and Gosselink, 2015).

The outflow from the equatorial lakes leads to strong seasonal inundation, characterized by annual flood pulses (Rebelo et al., 2012), that is further modified by local precipitation and evaporation (Mohamed and Savenije, 2014), leading to highly complex and seasonal behavior (Sosnowski et al., 2016). The interaction between upstream inflows, floodplain storage, and evapotranspiration makes the Sudd a highly nonlinear hydrological system in which changes in

inflow can produce disproportionately large changes in inundation extent (Mohamed et al., 2005).

Its extensive evapotranspiration fluxes significantly attenuate downstream discharge while simultaneously contributing to atmospheric moisture recycling, with implications for precipitation regimes across East and Central Africa. Wetland evapotranspiration contributes to regional moisture recycling by transferring water vapor from land surfaces back into the atmosphere, potentially influencing precipitation patterns beyond the wetland itself (Keys et al., 2016). This land–atmosphere coupling illustrates the role of large wetlands as components of regional climate regulation rather than isolated hydrological features (Mitsch and Gosselink, 2015).

Early modelling studies by Yates and Strzepek (1996), and Yates and Strzepek (1998) represent a foundational phase in the quantitative assessment of climate sensitivity within the Nile system. Using basin-scale hydrological models, these studies foregrounded the Sudd as a critical evaporative sink, demonstrating that relatively small perturbations in climate variables could produce disproportionately large impacts on water balance and downstream flows. However, these early approaches were constrained by coarse spatial resolution and simplified process representations, particularly in their treatment of wetland hydrodynamics and land–atmosphere feedback. Such limitations are common in early basin-scale hydrological models because wetlands often require finer spatial representation of inundation dynamics, vegetation processes, and evaporation variability than conventional river models provide (Tootchi et al., 2019).

More recent contributions have shifted towards integrating hydrological uncertainty with questions of governance and transboundary risk. Wheeler et al. (2018), for example, examine cooperative management strategies in the Eastern Nile Basin, highlighting how upstream hydrological variability propagates risk to downstream states. While not centered explicitly on the Sudd, such analyses implicitly depend on its regulatory function, as uncertainties in wetland evaporation and flow partitioning remain a key source of variability in basin-scale projections. This uncertainty is particularly important in transboundary river systems because changes in upstream hydrology, storage, and water losses can influence water availability and risk perceptions among downstream users (Pahl-Wostl, 2009).

Parallel to hydrological research, a rapidly expanding body of literature examines the Sudd's role in global methane emissions. Historically underrepresented in global greenhouse gas inventories, the wetland is now increasingly recognized as a major tropical methane source. Tropical wetlands are among the largest natural sources of atmospheric methane because prolonged inundation creates anaerobic conditions that promote microbial methane production (Saunois et al., 2020). This reassessment is largely driven by improved remote sensing and modelling techniques that capture the wetland's expanded and persistent inundation.

Studies by Dong et al. (2024), Albuhaisi et al. (2024), Hardy et al. (2023), and Pandey et al. (2021) suggest that earlier models significantly underestimated methane emissions due to incomplete representations of inundation extent. Satellite observations have substantially improved estimates of wetland methane emissions by providing more accurate measurements of seasonal and interannual changes in inundated area (Bloom et al., 2017). These findings align

with earlier regional assessments such as Lunt et al. (2019), which situate the Sudd within broader tropical African methane dynamics.

The emerging consensus points to a feedback loop in which increased inundation enhances anaerobic conditions, thereby amplifying methane production and reinforcing the wetland's significance in global climate systems. However, methane emissions depend not only on inundation extent but also on water depth, vegetation type, temperature, and carbon availability, creating substantial spatial and temporal variability in wetland greenhouse gas fluxes (Saunois et al., 2020). Therefore, future changes in the Sudd's hydrological regime may have implications not only for local flood risk and ecosystem services but also for regional and global climate feedback processes.

3.5 The water balance of the Sudd wetland

The Sudd wetlands constitute critical hydrological control within the White Nile system, functioning as a vast inland delta in which river inflow is substantially attenuated through storage and evapotranspiration processes. As one of the largest tropical wetlands globally, the Sudd has long attracted hydrological research aimed at quantifying its water balance and understanding the interplay between inflow, outflow, evaporation, and storage. Large wetlands such as the Sudd are important components of regional hydrological cycles because they regulate the timing, magnitude, and persistence of river flows through storage and delayed release processes (Mitsch and Gosselink, 2015). Across both early hydrometric studies and more recent remote sensing–based analyses, the literature converges on a set of broad empirical

regularities, while also highlighting persistent uncertainties arising from data limitations and spatial heterogeneity.

3.5.1 Conceptualization and key components of the water balance

The water balance of the Sudd is typically conceptualized as the equilibrium between inflow and precipitation on the one hand, and outflow, evapotranspiration, and changes in storage on the other. This approach follows the general hydrological water balance framework in which changes in storage represent the difference between incoming and outgoing fluxes over a defined period (Dingman, 2015)**.** In practice, precipitation plays a secondary role relative to river inflow, while lateral contributions—particularly from the Bahr el Ghazal—are often considered negligible at the basin scale (Sutcliffe and Parks, 1999; Howell et al., 1988).

The dominant inflow is delivered by the Bahr el Jebel (White Nile), measured upstream at Mongalla. Long-term records indicate relatively stable annual inflows in the range of approximately 45–50 $km^3\ yr^{-1}$, with a commonly cited mean near 49 $km^3\ yr^{-1}$ (Hurst and Phillips, 1938; Sutcliffe and Parks, 1999). This stability reflects strong upstream regulation by the Equatorial Lakes, which dampen interannual variability and produce a relatively smooth hydrograph compared to more rainfall-driven systems. The buffering influence of the Equatorial Lakes arises from their large storage capacity, which integrates seasonal rainfall variability before releasing relatively stable flows downstream (Sutcliffe and Parks, 1999).

Downstream, outflow measured near Malakal is significantly reduced, with estimates consistently indicating that only 20–30 $km^3\ yr^{-1}$ exits the wetland (Mohamed et al., 2005; Sutcliffe and Parks, 1999). This implies that roughly half of the incoming discharge is retained within the system. Despite variability in inflow, outflow remains comparatively stable, underscoring the Sudd's function as a hydrological buffer that moderates downstream discharge through floodplain storage and delayed release mechanisms (Santino et al., 2010). Such storage effects are characteristic of floodplain wetlands, where temporary retention of floodwater reduces peak flows and extends water availability beyond the flood season (Junk et al., 1989).

3.5.2 Evapotranspiration and hydrological losses

Evaporation and evapotranspiration represent the dominant loss term in the Sudd water balance. Most studies estimate total losses in the range of 20–30 $km^3\ yr^{-1}$, commonly approximated at around 28 $km^3\ yr^{-1}$ (Mohamed et al., 2005; van der Tol et al., 2004). These losses correspond to approximately 50–60% of total inflow, highlighting the Sudd's importance as a major source of atmospheric moisture within the Nile Basin. Wetland evapotranspiration represents a major pathway through which stored surface water is returned to the atmosphere, influencing both local water availability and regional climate interactions (Mitsch and Gosselink, 2015).

Early estimates, based on Penman-type formulations (Penman, 1963; Chan et al., 1980), assumed extensive open water surfaces and produced annual evaporation rates of approximately 2000–2150 $mm\ yr^{-1}$. However, subsequent research has emphasized the heterogeneous nature of the wetland, which includes papyrus swamps, seasonally inundated grasslands, and partially

dry areas. This heterogeneity reduces effective evaporation rates relative to open-water assumptions and complicates basin-wide estimation (Van der Tol et al., 2004). This distinction is important because vegetation transpiration and open-water evaporation respond differently to changes in radiation, humidity, wind, and water availability (Allen et al., 1998).

Advances in remote sensing have significantly improved the quantification of evapotranspiration. Studies by Mohamed et al. (2006) and Mohamed and Savenije (2014) demonstrate how satellite observations can capture spatial and temporal variability across the wetland, complementing sparse in situ measurements. These approaches have refined estimates of hydrological losses while also underscoring the sensitivity of evaporation to seasonal inundation patterns and vegetation dynamics**.** Remote sensing approaches have become particularly valuable in wetlands where field measurements are limited because they provide spatially continuous observations of inundation and vegetation conditions (Tootchi et al., 2019).

3.5.3 Storage dynamics and floodplain processes

A defining characteristic of the Sudd water balance is the importance of seasonal and interannual storage dynamics. The flooded area varies substantially, from approximately 30,000 km² under average conditions to over 100,000 km² during high-flow periods (Santino et al., 2010). Seasonal water level fluctuations of around 1–1.5 m drive cycles of inundation and recession across the floodplain.

During the wet season (typically July to November), increased inflow leads to expansion of inundated areas, increasing the surface available for evaporation. In the dry season (December

to April), peripheral areas gradually dry out, reducing evaporative losses and releasing stored water back into the system. This creates a nonlinear feedback mechanism: higher inflows expand flooded areas and enhance evaporation, thereby dampening downstream discharge variability. Such nonlinear relationships between inundation extent, evaporation, and discharge are common in large floodplain wetlands because hydrological responses are not proportional to changes in inflow (Junk et al., 1989).

Recent methodological developments, such as composite wetland mapping (Tootchi et al., 2019), further highlight the complexity of storage processes by distinguishing between regularly flooded wetlands and groundwater-driven wetlands. These approaches reinforce the importance of integrating surface water and subsurface processes in water balance assessments**.** Groundwater interactions are increasingly recognized as an important component of wetland water balances because they influence persistence of inundation after surface flows decline (Winter, 1999).

3.5.4 Methodological evolution and persistent uncertainties

The study of the Sudd's water balance has evolved from early hydrometric analyses to increasingly sophisticated, data-driven modelling approaches. Foundational works (e.g., Hurst and Phillips, 1938; Sutcliffe and Parks, 1989, 1999; Howell et al., 1988) established the basic structure of the system, including flood dynamics, storage capacity, and the relationship between inflow and outflow. Later syntheses (Sutcliffe and Brown, 2018) revisited these frameworks considering contemporary climate variability and hydrological change.

More recent research has integrated remote sensing and hydrological modelling to improve spatial coverage and parameter estimation, particularly for evaporation and inundation extent. While these advances have enhanced understanding, significant uncertainties remain. These stem from sparse and discontinuous gauge records, especially at key points such as Mongalla and Malakal, as well as the inherent difficulty of measuring spatially variable evaporation and storage changes. Uncertainty in wetland water balances is common because many wetlands lack long-term observations of water level, fluxes, and spatial inundation dynamics (Rosenberry and LaBaugh, 2008).

Moreover, the complex mosaic of vegetation and hydrological conditions complicates the separation of evaporation, transpiration, and open-water losses (Sutcliffe and Parks, 1999; Santino et al., 2010). Accurate partitioning of evapotranspiration components remains a major challenge in wetland hydrology because vegetation structure and water availability vary considerably across space and time (Allen et al., 1998).

3.5.5 Hydrological efficiency, intervention debates, and socio-political context.

Interpretations of the Sudd's water balance have long been embedded within broader debates over water resource management in the Nile Basin. Early hydrological studies framed the wetland as a zone of significant water "loss," emphasizing evaporation and transpiration as inefficiencies within the system (Hurst and Phillips, 1931, 1938; Butcher, 1938). These interpretations informed the technical and political rationale for large-scale hydraulic

interventions, most notably the Jonglei Canal project, initiated in 1978 to bypass the Sudd and increase downstream flows.

Subsequent research has increasingly challenged this framing. Improved estimates of evaporation and a better understanding of wetland functioning have called into question the assumption that such water losses are recoverable or "wasted." Instead, the Sudd is now widely recognized as providing essential hydrological regulation, ecological services, and climate feedback. Contemporary wetland science increasingly rejects the idea that evaporative losses represent simple inefficiencies, emphasizing instead the ecological and climatic functions supported by these fluxes (Mitsch and Gosselink, 2015).

Critical perspectives (e.g., Doran, 1991) further argue that the concept of "lost water" is not purely technical but reflects political and developmental agendas. Water accounting frameworks can therefore reflect competing values and priorities, particularly where ecological functions and downstream water demands are weighed against each other (Pahl-Wostl, 2009).

Contemporary debates—particularly considering recent extreme flooding—continue to reproduce these tensions. On the one hand, renewed discussions of large-scale interventions frame excess water as a resource to be controlled for flood mitigation and downstream use. On the other hand, critics emphasize the Sudd's role as a natural flood buffer and the risks that such interventions pose to ecological integrity and local livelihoods.

Overall, the literature presents a coherent but still evolving understanding of the Sudd's water balance. Annual inflows of approximately 45–50 km^3 are reduced to 20–30 km^3 at the outlet, with roughly half lost through evapotranspiration. This balance is mediated by extensive

floodplain storage and strong seasonal dynamics, which together produce relatively stable downstream flows despite variable inputs.

At the same time, the system remains characterized by significant uncertainties, particularly in relation to evaporation processes and spatial heterogeneity. Importantly, interpretations of the water balance are not neutral: they are closely linked to competing visions of water use, environmental management, and development in the Nile Basin. This highlights the broader principle that hydrological systems are socio-environmental systems, where physical processes and human decisions interact to shape outcomes (Sivapalan et al., 2012). Understanding the Sudd's water balance therefore requires not only technical analysis of hydrological processes but also critical engagement with the socio-political contexts in which these processes are interpreted and acted upon.

3.6 Flooding history, human vulnerability, and exposure

South Sudan, located in east-central Africa, is widely recognized as one of the world's most fragile and least developed states (UNEP, 2023). South Sudan consistently ranks among the most vulnerable countries to climate change, with extremely limited coping capacity (INFORM Risk Index, 2024; De Groeve et al., 2015). Multiple interacting factors exacerbate vulnerability to flooding, including geomorphological conditions, widespread poverty, shifts in livelihood systems (e.g., transitions from nomadic to more sedentary lifestyles), and the long-term impacts of protracted conflict (1983–2005; 2013–2018), which have disrupted social, economic, and

institutional structures. Decades of armed conflict have weakened governance systems, damaged infrastructure, constrained disaster preparedness, and undermined traditional mechanisms for managing environmental risks, thereby increasing exposure and reducing the capacity of communities to adapt to recurrent flooding (Johnson, 2016; Thomas-Jensen, 2011).

South Sudan is a global hotspot for flood risk, ranking seventh worldwide in terms of the proportion of its population exposed to river flooding, with risks projected to intensify under climate change (Borgomeo et al., 2023). Nowhere is this more evident than in the Sudd region, where flooding is both a defining environmental process and a major source of risk. The Sudd provides critical ecosystem services that sustain millions of livelihoods, including fisheries, grazing lands, and water resources. It also supports globally significant biodiversity, notably the largest terrestrial mammal migration on Earth, involving over six million animals such as white-eared kob, tiang, Mongalla gazelle, and Bohor reedbuck (African Parks, 2024; National Geographic, 2024).

Despite these benefits, flooding poses persistent challenges for local communities. Populations in the Sudd have historically adapted to seasonal inundation by balancing the advantages of water access (e.g., for livestock and agriculture) with strategies to reduce exposure, such as settling in relatively elevated areas. However, these adaptive practices are increasingly strained. Rural livelihoods remain highly climate-sensitive, with approximately 86% of households dependent on rain-fed agriculture and livestock (UNEP, 2013), making them particularly vulnerable to hydrological variability and extreme events. Conflict-related disruptions have further weakened these livelihood systems by restricting mobility, limiting access to grazing

areas and markets, and reducing the ability of pastoral and agro-pastoral communities to adjust seasonally to changing flood conditions (Leonardi, 2011; Deng, 2018).

Recent extreme flood events, combined with ongoing conflict and socio-political fragility, have significantly increased displacement and cross-border mobility. In South Sudan, conflict and environmental stressors interact through a reinforcing cycle: flooding displaces communities, while insecurity and armed violence constrain safe movement, access to resources, and the ability to relocate to lower-risk areas (Internal Displacement Monitoring Centre [IDMC], 2023; Raleigh, 2011). Migration is often mediated by existing social and kinship networks, yet predicting future movement remains highly uncertain due to the complex interplay of environmental, economic, and political drivers.

The proliferation of small arms and light weapons has further intensified vulnerability to flooding by increasing insecurity around displaced populations, restricting humanitarian access, and escalating competition over scarce resources such as dry-season grazing land, fishing areas, and safe settlement locations (Small Arms Survey, 2012; Mkutu, 2007). In flood-prone environments such as the Sudd, where mobility is an essential adaptation strategy, insecurity can transform adaptive movement into forced displacement, thereby increasing exposure and weakening livelihood resilience.

The literature highlights a critical gap in empirically grounded frameworks that explicitly link flood risk, exposure, and migration dynamics, limiting the ability to anticipate and respond to climate-induced mobility. More broadly, the literature points to a rapid and uneven increase in population exposure to flood risk, particularly in floodplain and wetland environments where climate change, population growth, and limited infrastructure converge. These challenges are

especially acute in contexts such as South Sudan, where data scarcity, institutional fragility, and conflict-related disruptions hinder accurate assessment of exposure in complex hydrological systems like the Sudd.

In the Sudd region, flooding thus represents a dual reality: it underpins essential ecosystem services and livelihoods while simultaneously posing significant hazards. Although local communities have long adapted to seasonal flooding, increasing exposure, reduced coping capacity, and compounding socio-political stressors are intensifying vulnerability. The interaction between climate hazards and conflict dynamics demonstrates that flood risk in South Sudan cannot be understood purely as a hydrological challenge but must also be examined as a socio-political process shaped by insecurity, displacement, and uneven access to adaptation resources (Barnett and Adger, 2007). Addressing these challenges requires more context-specific, data-informed approaches that integrate hydrological processes with social dynamics to better understand and manage flood risk in highly vulnerable wetland systems.

In summary, the literature shows that South Sudan—and particularly the Sudd region—faces high and increasing flood risk due to the interaction of climatic, hydrological, and socio-political factors. While flooding sustains vital ecosystem services and livelihoods, it also drives growing vulnerability, displacement, and uncertainty. The legacy of armed conflict and the continued availability of small arms have reduced institutional capacity and increased competition over land and resources, making flood-affected communities less able to absorb, adapt to, and recover from hydrological shocks (Johnson, 2016; Small Arms Survey, 2012). Existing research highlights significant gaps in linking flood dynamics with human exposure

and migration, underscoring the need for integrated, context-sensitive approaches to flood risk assessment and management.

3.7 An ecological paradox of the Sudd: geopolitical backdrop and socio-economic system of the Sudd Nile

3.7.1 Geopolitical backdrop of the Sudd Nile

In this thesis, the term “Sudd Nile” is introduced as an analytical designation for the reach of the White Nile system extending from Mongalla (the upstream entry point into the Sudd wetland) to Malakal (the downstream exit of the Sudd wetland system). This segment encompasses the hydrologically and socio-ecologically transformed river–wetland continuum dominated by the Sudd wetland. The term does not replace established nomenclature such as the White Nile, Bahr el Jebel, or Bahr el Zeraf, but is used to emphasize the integrated socio-hydrological system within which river flow, floodplain storage, evapotranspiration, and human adaptation processes are tightly coupled. This framing aligns with socio-hydrological approaches that conceptualize water systems as coupled human–environment systems shaped by reciprocal interactions between hydrological processes and societal responses (Sivapalan et al., 2012).

This section outlines the geopolitical backdrop of the Sudd Nile, situating contemporary hydro-political dynamics within their longer historical trajectory. Understanding present and future contestations over water resources and flood management in the Sudd requires engagement with enduring tensions between ecological functions, infrastructural ambitions, and competing regional interests (Schouten and Bachmann, 2020). Dynamics of contemporary (and future) geopolitics of the Sudd cannot be fully comprehended without unwinding the historical layers of contestation and conflict around water projects and desires to control the flow of the Sudd (Schouten and Bachmann, 2020). Large river systems such as the Nile have historically been shaped not only by hydrological processes but also by political relationships between upstream and downstream societies, particularly where water scarcity and development objectives intersect (Allan, 2003).

For a century and a quarter, different external ventures—pioneers, explorers, imperialists, adventurers—all encountered in the Sudd a formidable buffer to the realization of their various projects of control (Schouten and Bachmann, 2020). As the Nile flows, the Sudd presents a complex ecological paradox. On the one hand, the Sudd has been a lifeline (Howell, 1983; Howell et al., 1988; Evans-Pritchard, 1940) for indigenous communities, not only through the provision of its ecosystem services but also as a barrier against historical imperial attempts of domination over Indigenous communities. The role of wetlands as both ecological resources and territorial barriers has been documented in many African contexts, where difficult terrain constrained external control while sustaining local livelihood systems (Adams, 1992).

On the other hand, the Sudd has been an impediment to various foreign conquests and a source of devastating flooding to the detriment of environmental health and human flourishing. This

dual character—simultaneously a lifeline and a constraint—captures the ecological paradox of the Sudd. While it provides essential ecosystem services and supports human resilience, it also generates recurrent flooding that can disrupt settlements and livelihoods. These tensions are central to contemporary debates on flood management and water resource development. Such tensions reflect broader debates in wetland governance, where wetlands are valued simultaneously as productive ecosystems and spaces requiring management because of perceived hazards (Mitsch and Gosselink, 2015).

As a lifeline for local populations, the Sudd has been a staple resource that local communities have depended on for survival and stability over a long period of time, just as Egypt's existence depends on the Nile flow. Certainly, as the Greek historian Herodotus wrote, "Egypt is a gift of the Nile," having observed that the entire civilization, from its fertile land to its water supply, depended on the Nile River's annual flooding, which deposited life-sustaining silt and made life possible in the surrounding desert. As the Nile River is central to Egypt's existence, the Sudd wetland is central to South Sudan's ecology and culture. Indeed, South Sudan is a gift of the Sudd.

The comparison between Egypt and the Sudd highlights two different but connected Nile relationships: downstream dependence on river discharge for irrigation and upstream dependence on floodplain ecosystems for livelihoods, mobility, and cultural practices (Tvedt, 2010). The Sudd wetland seasonal flooding has been vital for South Sudan's local communities since their settlement in what is now South Sudan, providing essential resources for survival and cultural preservation through fishing, pastoralism, and hunting in the largest habitats of mammal migration on Earth that depend on the Sudd ecosystem services.

However, as an impediment to the spread of globalization and a constraint on flourishing of the local communities, the Sudd has historically provided a buffer against some of the great imperial quests in the Southern Sudan region, now South Sudan, and had caused major floods that were disruptive to local populations. The Sudd's wild and thick floating vegetation makes navigation through the White Nile channels extremely difficult. Historical accounts of Nile exploration repeatedly describe the Sudd as a major navigational obstacle due to dense vegetation, shifting channels, and difficult hydrological conditions (Howell and Allan, 1994).

The Sudd naturally blocked the mighty Roman expedition's attempt to reach the sources of the Nile River during the reign of Emperor Nero in 60–61 AD. That party of Roman soldiers could not get beyond the Sudd, which marked the limit of Roman penetration into equatorial Africa. The Sudd also thwarted Egyptian expeditions seeking the source of the Nile. Equally, the Sudd blocked Victorian explorers' attempts to discover the sources of the White Nile. In the words of the Victorian Africanist Sir Harry Johnston, the quest for this source had become "the greatest single geographical secret after the discovery of America" (Johnston, 1905, p. vii).

Between 1858 and 1877, explorers including Burton, Speke, Grant, Baker, Livingstone, and Stanley travelled through Africa to investigate the equatorial lakes that formed the headwaters of the White Nile (Howell and Allan, 1994). These expeditions illustrate the extent to which Nile geography became connected to imperial scientific competition and territorial ambitions during the nineteenth century (Tvedt, 2010).

The Sudd thick vegetation also impeded Great Britain's colonial officers and Egyptian slave traders from reaching the interior villages of Southern Sudan territory and using the Nile to transport slaves across continental Africa. For a century and a quarter, the Sudd has been at the

center of Egyptian attempts to control the Nile Valley. The Sudd was at the heart of the former British–Egyptian Century Storage Concept, through which water would be stored in the Great Lakes of Equatorial Africa where evaporation is balanced by rainfall (Howell and Allan, 1994). The Century Storage Concept reflected colonial-era engineering visions that prioritized maximizing downstream water availability through control of upstream hydrological systems (Tvedt, 2010). As part of this concept, Egypt's search for additional water contributed to proposals for reservoirs, regulators, and diversion structures intended to modify the hydrology of the White Nile system.

This century-long struggle for control of the unyielding nature of the Sudd eventually led to the genesis of a diversion canal to circumvent the Sudd and channel additional water to Sudan and Egypt for agricultural and industrial uses. In 1904, William Garstin adopted the suggestion of J. S. Beresford, former Inspector General of Irrigation in India, to construct a direct canal east of the Sudd (later known as the Jonglei Canal) capable of carrying additional water downstream (Howell and Allan, 1994).

The construction of the Jonglei Canal began in 1978, but the second Sudanese civil war brought the works to a halt in 1984 when approximately 240 km of the planned 360 km canal had been excavated. A series of studies followed, including Eagleson and Chan (1980) and Eagleson and El-Hemry (1980), investigating the hydrological implications of canalization. The Jonglei Canal became one of the most prominent examples of how hydrological engineering projects can become entangled with questions of sovereignty, ecological transformation, and local livelihoods (Howell, 1994).

In “Why hydro-politics will shape the 21st Century,” water has been called the “next oil,” and in coming decades, water supply has the potential to influence geopolitics, diplomacy, and conflict (BBC, Lufkin, 2017). Following the signing of the Comprehensive Peace Agreement (CPA) between the Sudan government and SPLA/M in 2005, Egypt became more deliberate in its interest in reviving the Jonglei Canal. In 2022, Egypt started dredging Bahr el Naam, a tributary of the Bahr el Ghazal system in South Sudan, to “control the flood.” However, there are no publicly available comprehensive scientific assessments demonstrating the environmental and social consequences of such interventions. Large-scale river engineering projects increasingly require integrated environmental and social assessments because interventions can alter hydrological connectivity, sediment transport, biodiversity, and livelihood systems (World Commission on Dams, 2000).

In summary, these tensions reflect competing priorities: downstream states emphasize water supply augmentation, while local and upstream perspectives stress ecological sustainability, flood-dependent livelihoods, and socio-cultural resilience. The persistence of the Jonglei Canal debate, despite decades of conflict and environmental change, underscores the durability of these competing visions. The literature portrays the Sudd as a coupled human–natural system shaped by intersecting hydrological, ecological, and geopolitical processes. Historically, it has functioned both as a barrier to external control and as a foundation for local livelihoods. Such systems are increasingly understood through political ecology approaches that examine how environmental processes interact with power, governance, and competing development priorities (Robbins, 2012).

In the present, it remains a contested space where technocratic water management strategies confront complex socio-ecological realities. Contemporary transformations—including intensified flooding, climatic variability, and renewed infrastructural interest—are reshaping the terms of this debate. Yet these developments remain deeply rooted in historical patterns of hydro-political contestation. Addressing the challenges of the Sudd therefore requires integrated approaches that bridge hydrology, ecology, and political economy, recognizing the wetland's central role in both regional geopolitics and local resilience.

3.7.2 Socio-economic system of the Sudd Nile

The socio-economic systems of the Sudd are fundamentally shaped by the seasonal dynamics of its wetland ecology. Local communities conceptualize the Sudd as a life-sustaining system governed by cyclical flooding patterns, which simultaneously enable and constrain human activity. This duality reflects the wetland's capacity to both sustain livelihoods and generate risk, depending on the magnitude and variability of flooding. Such relationships between ecological cycles and human adaptation are characteristic of floodplain societies, where communities have historically developed livelihood strategies around predictable patterns of inundation and resource availability (Junk et al., 1989).

Seasonal inundation replenishes soil moisture, supports pasture regeneration, and sustains fisheries, forming the ecological basis of food security and economic productivity. In this context, moderate and predictable flooding is beneficial, underpinning agricultural yields, livestock productivity, and fish availability. Flood pulses enhance ecological productivity by transporting nutrients, renewing grazing resources, and supporting aquatic food webs in

wetland environments (Junk et al., 1989; Mitsch and Gosselink, 2015). However, extreme flooding events—such as those observed in the 1960s and more recently between 2019 and 2024—can exceed adaptive thresholds, leading to displacement, asset loss, and livelihood disruption.

The Sudd is widely understood in literature as a coupled socio-ecological system, in which hydrological variability shapes patterns of livelihoods, settlement, and social organization (Howell et al., 1988; Johnson, 1994; Schouten and Bachmann, 2020; UNEP, 2022). Socio-hydrological perspectives emphasize that human societies do not simply respond to water variability but actively reshape their relationship with water through institutions, mobility, and resource management practices (Sivapalan et al., 2012).

Livelihood systems have historically evolved in close alignment with the flood pulse of the Nile, giving rise to highly adaptive strategies that integrate agro-pastoralism, fishing, and seasonal mobility. Nilotic communities—including the Dinka, Nuer, Shilluk, and others—practice transhumant pastoralism, moving livestock between dry-season grazing areas in the toic (seasonally flooded grasslands) and higher ground during the rainy season. These movements are synchronized with hydrological cycles, enabling efficient use of spatially and temporally variable resources. Pastoral mobility in African floodplain environments functions as an adaptation strategy that allows households to track changing distributions of water, pasture, and disease risk across landscapes (Little et al., 2001).

In the dry season, pastoralists move close to the seasonally flooded grasslands as the wetland flooding regime has defined the livelihoods of millions of people who live in the Sudd region.

Howell et al. (1988, p. 226) describe the economy of the two major Nilotic ethnic groups in the Sudd region:

> "To differing degrees, the economy of the Dinka and Nuer involves transhumant animal husbandry, moving according to the seasons over high land, intermediate land and toic/swamps, in association with crop production restricted to the marginally better drained land during the rains, supplemented by fishing in the rising and receding waters of the rivers, and hunting the abundant wildlife during the dry season."

Crop cultivation is typically concentrated on relatively elevated and better-drained soils during the rainy season, while fishing intensifies during periods of rising and receding floodwaters. Hunting and gathering further supplement subsistence. These diversified livelihood portfolios reduce dependence on any single environmental resource and represent a common resilience strategy in variable environments (Scoones, 1998). Such practices are embedded within customary institutions that regulate access to land and water, facilitating negotiated and adaptive resource use in a highly dynamic environment (Deng, 2010). In the Sudd context, these institutions include the authority of customary chiefs, clan and lineage elders, and community leaders who oversee access to fishing grounds, grazing areas, dry-season cattle camps (toic), and floodplain cultivation areas. They also include customary rules governing seasonal livestock movements, negotiated sharing of water points, protection of important fishing locations, and community-based mechanisms for resolving disputes over land and water use.

Among Nilotic communities, such as the Dinka and Nuer, these arrangements have historically enabled communities to adapt to seasonal flooding by coordinating mobility, resource access, and reciprocal obligations. Customary institutions often play a central role in managing

common-pool resources where formal governance systems have limited reach, particularly in rural and remote areas (Ostrom, 1990).

Social organization has therefore historically been decentralized, with authority distributed across kinship and lineage systems. Despite their resilience, these socio-economic systems have been significantly affected by protracted conflict and underdevelopment. The Sudd has experienced repeated disruptions due to civil wars, which have caused displacement, loss of assets, and breakdown of local economies (Johnson, 1994). Conflict can weaken environmental adaptation by disrupting mobility routes, restricting resource access, and eroding social institutions that traditionally support collective resource management (Le Billon, 2001). At the same time, limited infrastructure, weak market integration, and minimal state investment have reinforced the predominance of subsistence-oriented livelihoods (UNEP, 2022). These conditions have contributed to persistent vulnerability, constraining opportunities for economic diversification and development. Low infrastructure coverage also increases exposure to climate hazards because communities have fewer alternatives for accessing services, markets, and emergency support during periods of flooding (IPCC, 2022).

In the contemporary period, local economies remained heavily dependent on pastoralism, fisheries, and small-scale agriculture. However, these systems are increasingly under pressure from environmental variability and socio-economic change. Intensified and prolonged flooding in recent years has generated new challenges, including reduced mobility, livestock mortality, and declining agricultural productivity (Sutcliffe and Parks, 1999; UNEP, 2022). Changes in flood duration can be particularly disruptive because pastoral and agricultural systems depend not only on flood magnitude but also on the timing and predictability of inundation and

recession (Junk et al., 2013). These impacts are compounded by population displacement and insecurity, which undermine traditional coping mechanisms and adaptive capacity. Displacement can transform previously adaptive mobility practices into involuntary movements, increasing vulnerability by separating households from livelihood resources and social support networks (McLeman, 2017).

Demographic uncertainty further complicates the socio-economic characterization of the Sudd. Reliable population data is limited due to the absence of a recent national census and the logistical challenges of surveying mobile and remote populations. Estimates vary significantly: while UNESCO (2017) suggests approximately one million inhabitants within the Sudd, extrapolations from earlier census data indicate that the population may range between three and five million. This uncertainty reflects high levels of mobility, displacement, and environmental exposure, all of which are central features of the region's socio-economic dynamics. Population estimates in floodplain environments are particularly difficult because seasonal mobility, displacement, and temporary settlements challenge conventional census approaches based on fixed locations (Carr-Hill, 2013).

Governance in the Sudd operates through a hybrid system combining formal administrative structures and customary authority. South Sudan's administrative hierarchy—comprising states, counties, payams, and bomas—coexists with traditional leadership systems, including paramount chiefs and local headmen. These overlapping institutions play a key role in managing resource access, mediating conflicts, and coordinating seasonal movements. Hybrid governance arrangements are common in areas where state institutions have limited capacity, with customary authorities often providing essential functions in conflict resolution and natural

resource management (Boege et al., 2009). However, governance capacity remains limited, particularly in remote and flood-affected areas, constraining effective service delivery and long-term development planning.

Overall, the socio-economic systems of the Sudd reflect a complex interplay between ecological variability, livelihood adaptation, and structural constraints. While local communities have developed sophisticated strategies to navigate environmental uncertainty, these systems are increasingly strained by extreme climatic events, demographic pressures, and persistent underdevelopment. Understanding these dynamics requires moving beyond hazard-based approaches toward vulnerability frameworks that consider exposure, sensitivity, and adaptive capacity together (Adger, 2006). Understanding these dynamics is essential for situating the Sudd within broader discussions of vulnerability, resilience, and sustainable development.

3.8 The Sudd as a socio-hydrological system

The socio-hydrological dynamics of the Sudd wetland have been explored from multiple perspectives, highlighting the complex interactions between flooding, human livelihoods, and governance. Early work by Howell (1988) examined how livelihoods and social systems are shaped by flood regimes, particularly in relation to water engineering interventions. Hydrology-focused studies, such as Rebelo et al. (2012), have illustrated how seasonal inundation underpins local livelihoods, while also highlighting the socio-economic consequences of altering flood regimes. More recent research has increasingly integrated human perceptions and adaptive strategies: Zeleke et al. (2024) investigates local perceptions of environmental change

associated with flooding and climate variability, linking these to broader socio-hydrological adaptation patterns. This evolution reflects a broader shift in water research from viewing hydrology as an exclusively physical process toward understanding water systems as coupled human–environment systems in which societies both influence and respond to hydrological change (Sivapalan et al., 2012).

Governance and regional water management play a critical role in shaping these interactions. Di Vittorio and Georgakakos (2021) situate hydrologic behavior within broader social and management contexts, noting the socio-economic benefits of maintaining natural flooding patterns. At the regional scale, the Nile Basin Initiative (NBI) serves as a key actor, having produced a comprehensive four-part Sudd Wetland Monograph (2022–2025) that details eco-hydrological planning models used by the ten Nile countries for water-sharing and management decisions. Such basin-scale approaches increasingly recognize that wetland management cannot be separated from questions of governance, institutional coordination, and competing water priorities among states and communities (Allan, 2003; Zeitoun and Warner, 2006).

The Sudd has frequently been conceptualized as a tightly coupled socio-ecological system in which hydrological dynamics and human livelihoods are deeply intertwined. Central to this understanding is the seasonal variability of the White Nile, whose flood regimes structure patterns of mobility, production, and settlement across the region. Drawing on the flood pulse concept, scholars have emphasized how cyclical inundation creates ecological conditions that sustain fisheries, grazing lands, and flood-recession agriculture (Bayley, 1995). The flood pulse concept highlights that seasonal flooding is not simply a disturbance but a fundamental

ecological process that maintains productivity and biodiversity in river–floodplain systems (Junk et al., 1989).

These environmental rhythms are not merely biophysical processes but are embedded within social organization, shaping pastoral transhumance, cattle-based economies, and kinship structures (Johnson, 2019; Leauthaud et al., 2013). In this sense, the Sudd exemplifies key insights from Human Ecology, where environmental variability acts as a primary structuring force in social life. Human ecology perspectives emphasize that livelihoods in highly variable environments emerge through long-term adaptation between cultural practices, institutions, and ecological constraints (Berkes and Folke, 1998). At the same time, a growing body of literature highlights the reciprocal, though uneven, influence of human activity on wetland dynamics. Local practices such as controlled burning, grazing, and fishing contribute to vegetation patterning, nutrient cycling, and localized ecological change, suggesting the presence of feedback mechanisms within the system (Leauthaud et al., 2013).

These dynamics align with emerging frameworks in Socio-hydrology, which conceptualize water systems and human societies as co-evolving through iterative interactions (Sivapalan et al., 2012). Socio-hydrological studies emphasize that these interactions are often nonlinear, meaning that small changes in environmental or social conditions can produce disproportionate consequences over time (Pande and Sivapalan, 2017). However, scholars caution against overstating this reciprocity. While human activities shape ecological processes at local scales, the large-scale morphology and hydrological functioning of the Sudd remain predominantly governed by climatic variability and basin-scale hydrological processes (Le Roy Poff et al., 1997). As such, the relationship is better understood as asymmetrical, with hydrology exerting

a stronger structuring influence on society than vice versa. This asymmetry is consistent with observations from large floodplain systems where ecological processes operate at spatial and temporal scales beyond the influence of individual communities (Ward et al., 1999).

Early assessments suggest that diverting water away from the wetlands would have reduced flood extent, undermining the ecological basis of pastoralism and fisheries (Howell, 1988). Such large-scale schemes foreground the importance of Political Ecology, which draws attention to how power, governance, and external actors reshape human–environment relations (Tvedt, 2004). Political ecology approaches emphasize that environmental interventions are rarely purely technical decisions; rather, they reflect competing interests, knowledge systems, and distributions of political power (Robbins, 2012). In the Sudd, the system is therefore not only co-evolving internally but is also increasingly mediated by state agendas, conflict dynamics, and international hydro-politics.

Comparable socio-hydrological dynamics have been documented in major floodplain systems such as the Okavango Delta (Kgathi et al., 2006; Mendelsohn et al., 2010), the Mekong Delta (Biggs et al., 2020; Trung et al., 2020), and the Amazon Basin (Castello et al., 2013; Junk et al., 2011), where livelihoods remain closely attuned to hydrological variability despite increasing external intervention.

Through these systems, researchers have demonstrated that flood-dependent communities often maintain adaptive practices through mobility, livelihood diversification, and flexible resource use rather than through complete control of environmental variability (Berkes and Folke, 1998; Scoones, 1998). What distinguishes the Sudd, however, is less its uniqueness than the relative persistence of these interactions under conditions of limited infrastructural control and ongoing

socio-political instability. In contrast to heavily engineered systems, where hydrology is increasingly regulated, the Sudd retains a high degree of dependence on natural flood regimes, intensifying the immediacy of human–environment linkages. Thus, rather than framing the region as exceptional, literature increasingly positions it as a critical case for understanding how socio-ecological systems function under conditions of variability, constraint, and external pressure.

Recent scholarship has further complicated earlier understandings of human–water interactions in systems such as the Sudd by foregrounding the role of uncertainty, external intervention, and cross-scale dynamics. Resilience scholarship argues that such systems should not be understood as static equilibria but as dynamic systems capable of reorganization following disturbance (Holling, 1973; Folke, 2006). Studies in Socio-hydrology have increasingly emphasized non-linear feedback and the co-production of risk, particularly under conditions of climatic variability and political instability (Duvail et al., 2017; Orr et al., 2022). At the same time, advances in floodplain ecology highlight how alterations in flow regimes—whether due to climate change or upstream interventions—can trigger cascading ecological and livelihood impacts (Grantham et al., 2022).

Changes to natural flow regimes can alter sediment transport, nutrient cycling, habitat availability, and ecosystem productivity, with consequences that extend beyond hydrology into social and economic systems (Poff et al., 1997). From a governance perspective, work in Political Ecology has shifted attention toward the ways in which water management decisions are embedded in asymmetrical power relations, often privileging large-scale economic or state interests over local adaptive systems (Zeitoun et al., 2016; Lopez-Hoffman et al., 2026). These

perspectives collectively move beyond equilibrium-based models, instead framing the Sudd as a system increasingly shaped by external pressures and contested knowledge systems.

Overall, literature underscores the need to view the Sudd as a dynamic, non-linear system shaped by co-evolutionary processes, cross-scale influences, and contested governance. Such a perspective is particularly important for flood-risk research because vulnerability emerges not only from hydrological hazards but also from the interaction between exposure, livelihoods, institutions, and adaptive capacity (Adger, 2006).

3.9 Summary of the study area literature review

The Sudd wetland is conceptualized as a highly dynamic socio-hydrological system in which hydrological processes, ecological functions, and human systems are tightly interconnected but asymmetrically structured. This perspective reflects the broader socio-hydrological understanding that water systems and societies co-evolve through reciprocal but unequal interactions over time (Sivapalan et al., 2012).

At its core, the Sudd operates as a flood-pulse-driven wetland, regulated primarily by White Nile inflows from the Equatorial Lakes, with seasonal inundation sustaining biodiversity, pastoralism, fisheries, and flood-recession agriculture. The flood pulse concept emphasizes that seasonal flooding is a fundamental ecological process that maintains productivity, nutrient exchange, and biodiversity in river–floodplain systems (Junk et al., 1989).

However, recent literature highlights a transition from this natural rhythm toward a “new normal” of prolonged and multi-year flooding, driven largely by upstream lake level increases, climate variability, and delayed flood wave propagation. Such changes illustrate how alterations in climate conditions and upstream hydrological processes can modify the timing, duration, and magnitude of wetland inundation (Poff et al., 1997).

Hydrologically, the Sudd functions as a major regional regulator within the Nile Basin, characterized by complex water balance dynamics and extreme evapotranspiration losses (about 50% of inflow), which attenuate downstream discharge while supporting atmospheric moisture recycling. Large tropical wetlands such as the Sudd act as important hydrological regulators because they store water, delay runoff transmission, and return substantial moisture to the atmosphere through evapotranspiration (Mitsch and Gosselink, 2015).

Its “long-memory” storage capacity allows flood conditions to persist across years, even under normal local rainfall, reinforcing its role as both a buffer and amplifier of hydrological extremes. The persistence of wetland conditions reflects the importance of storage effects, where previous hydrological conditions influence present water availability and ecosystem functioning (Ward et al., 1999). At the basin scale, the Sudd is therefore critical for hydro-climatic regulation, transboundary water governance, and climate system interactions. This significance extends beyond hydrology because wetlands increasingly influence regional climate processes through feedback involving vegetation, surface water, and atmospheric moisture exchange (Mitsch and Gosselink, 2015).

From a socio-hydrological perspective, the Sudd exemplifies a coupled human–water system shaped by nonlinear feedback, co-evolution, and emergent dynamics. Socio-hydrology

emphasizes that water systems cannot be understood independently from human institutions, decisions, and adaptive behaviors (Sivapalan et al., 2012). Flood regime's structure livelihoods, mobility (e.g., pastoral transhumance), and social organization, while human responses—such as settlement shifts, local ecological practices, and coping strategies—feed back into the system. Flood-dependent societies often develop mobility, diversification, and institutional arrangements that allow them to respond to spatial and temporal variability in environmental resources (Berkes and Folke, 1998; Scoones, 1998). However, this relationship is asymmetrical, with large-scale hydrology exerting stronger control over social systems than vice versa. In large floodplain systems, ecological processes operating at regional scales often constrain human adaptation options, particularly where infrastructure and institutional capacity are limited (Ward et al., 1999).

Increasingly, the literature frames the Sudd through resilience and co-evolutionary frameworks, emphasizing absorptive, adaptive, and transformative capacities, while also recognizing the potential for tipping points, surprises ("Black Swan" events), and system reconfiguration. Resilience theory highlights that social–ecological systems may shift between different states when disturbances exceed existing adaptive capacities (Holling, 1973; Folke, 2006).

At the same time, the system is embedded within broader political, historical, and economic contexts, where conflict, governance, and external interventions (e.g., the Jonglei Canal) reshape human–environment relations. Political ecology perspectives emphasize that environmental changes and interventions are shaped by power relations, competing interests, and unequal access to resources (Robbins, 2012). The long-standing debate over the canal reflects a fundamental tension between hydrological efficiency (reducing evaporation losses,

increasing downstream flow) and local socio-ecological sustainability, with contemporary perspectives increasingly emphasizing trade-offs and risks to livelihoods. Large-scale water engineering projects frequently involve trade-offs between economic objectives, ecological functions, and local livelihood systems (World Commission on Dams, 2000).

A growing body of research situates the Sudd within global flood risk and vulnerability frameworks, highlighting that wetland and floodplain populations—particularly in low-income regions—are disproportionately exposed yet underrepresented in data and modeling. Flood vulnerability is shaped not only by hazard exposure but also by socioeconomic conditions, governance capacity, and ability to adapt (Adger, 2006).

South Sudan emerges as a global hotspot of flood vulnerability, where limited infrastructure, poverty, and conflict amplify exposure. Climate-related risks are particularly severe where environmental hazards interact with conflict, weak institutions, and limited adaptive capacity (IPCC, 2022). Despite advances in global flood modeling, population exposure in complex wetlands like the Sudd remains poorly quantified, representing a critical knowledge gap. This challenge reflects broader limitations of global flood models, which often struggle to represent fine-scale exposure patterns, local hydrological processes, and mobile populations (Tellman et al., 2021). This gap is especially important given the rising significance of climate-induced migration. The literature shows that environmental change—particularly recurrent extreme flooding (e.g., 2019–2024 events)—is increasingly driving internal displacement and cross-border migration, often interacting with conflict and social fragility. Migration responses to environmental change are rarely caused by climate factors alone but emerge from interactions between hazards, livelihoods, conflict, governance, and household decision-making

(McLeman, 2017). While migration has long been part of human adaptation to environmental variability, current conditions suggest that communities in the Sudd are being pushed beyond their adaptive capacity, yet there remains limited integration of flood risk, exposure, and migration modeling. This highlights the need for approaches that connect physical hazard modelling with social vulnerability and mobility dynamics (Black et al., 2011).

Emerging research frontiers further expand the conceptualization of the Sudd by identifying it as a significant global methane source, reassessing upstream–downstream hydrological connectivity, and addressing key uncertainties such as flood wave transit times, rainfall vs. inflow attribution, and groundwater interactions. Recent satellite-based studies have demonstrated that tropical wetlands, including the Sudd, may contribute substantially to global methane emissions because of persistent inundation and anaerobic conditions (Pandey et al., 2021).

Methodologically, the field is shifting toward integrated "data fusion" approaches, combining remote sensing, hydrological modeling, and machine learning to better capture system complexity. Data integration approaches are increasingly important for wetlands because they combine the spatial coverage of remote sensing with the process representation of hydrological models (Rebelo et al., 2012).

In summary, the literature converges on viewing the Sudd as a globally significant, climate-sensitive, and socially vulnerable system, where intensifying hydrological extremes, strong upstream controls, and limited adaptive capacity intersect. Such systems are increasingly recognized as coupled social–ecological systems requiring integrated analysis across hydrology, ecology, and human geography (Folke, 2006).

Literature underscores the need to view the Sudd as a dynamic, non-linear system shaped by co-evolutionary processes, cross-scale influences, and contested governance. While its ecological and hydrological functions remain indispensable, critical gaps persist in linking physical flood dynamics with human exposure, vulnerability, and migration, underscoring the need for integrated socio-hydrological and empirical approaches to inform policy and resilience planning.

The Sudd as a case study represents an analytically important and policy-relevant case for three reasons. First, it is globally significant as one of the largest wetlands in the world and a key component of the Nile Basin, meaning its hydrology has regional implications. Large wetlands are increasingly recognized as critical components of global biodiversity conservation, hydrological regulation, and climate processes (Mitsch and Gosselink, 2015).

Second, it exemplifies extreme data scarcity combined with high vulnerability. This makes it an ideal case for testing the limits of global models and highlighting where they fail. Data scarcity remains a major challenge in many vulnerable regions because remote and conflict-affected areas often lack long-term hydrological and demographic observations needed for modelling (Tellman et al., 2021).

Third, the Sudd presents a unique socio-hydrological system where livelihoods are deeply intertwined with flooding. This allows examination not only of flood impacts but also of how flooding functions as both a hazard and a resource—something often overlooked in conventional risk frameworks. This distinction is consistent with resilience-based approaches that recognize environmental variability as both a source of risk and a foundation for ecosystem productivity and livelihood adaptation (Berkes and Folke, 1998).

CHAPTER 4

4 GEOSPATIAL ANALYSIS OF POPULATION EXPOSURE TO FLOODING IN THE SUDD REGION

This chapter provides a first comprehensive insight into flood exposure in South Sudan, and the Sudd region. The chapter addresses the first research questions: How can geospatial mapping techniques be used to characterize population exposure to flood hazards in the Sudd region of South Sudan? What is the extent of population exposure to flood hazards across the Sudd region? The chapter also provides a brief literature review, bringing together existing studies on the hydrology of the Sudd to lay a ground knowledge for the evolution of the flood hazards and human exposure. This chapter was submitted to the Journal of Flood Risk Management on April 24th, 2025, and was published on January 4th 2026. Geospatial Analysis of Population Exposure to Flooding in the Sudd Region, South Sudan - Chol - 2026 - Journal of Flood Risk Management - Wiley Online Library. The chapter was co-authored by Jim W. Hall, Kenneth

Strzepek, Kevin Wheeler, Mark Bernhofen, and Courtney Di Vittorio, who provided conceptual guidance and reviewed the manuscript.

Supplementary figures follow the reference list of this chapter.

Abstract

The Sudd wetland in South Sudan extends over 90,000 km2. Large-scale flood events in recent years (2019-2022) are said to have led to the displacement of an estimated 1.8 million people in total. However, these estimates are approximate and to date there has not been a systematic analysis of population exposure to flooding in the Sudd region. This study seeks to address this gap by using global flood modelling, satellite observations of flood extent, and global gridded population datasets to analyze population exposure. Recognizing the inevitable limitations of these datasets, the study intersects all the available global flood mapping and population datasets. The results indicate that 0.8-2.9 million people are currently exposed to the 100-year return period flood extent, depending on the flood model and population dataset used. Aggregated results of the model agreement intercomparison indicate that all five global models agree on key flood-prone areas within and around the Sudd, which is further corroborated with satellite flood observations. Intercomparison of the population density among the four georeferenced population products demonstrates that WorldPop and GHSL-Pop population distributions better represent the patterns of the Sudd rural settlements that are typically in forms of clusters. The uncertainty in exposure estimates is attributable to variations in both flood outlines and geospatial population estimates. These findings provide hitherto unavailable insights into flood exposure in South Sudan, to inform flood management decisions and disaster reduction responses in the Sudd region. This study demonstrates the global significance of model intercomparison as best practice for any flood exposure analysis to underpin policy and decision-making in Africa and other data-scarce regions.

4.1 Introduction

Whilst more than a billion people across the world depend on wetlands for their livelihoods (United Nations, 2023), population exposure to flood hazards around wetlands and within floodplains

has been increasing rapidly (Andreadis et al., 2022; Rentschler et al., 2022; Jongman et al., 2012; Rentschler et al., 2023). Though global exposure to flood risk is increasingly studied (McMichael et al., 2020; Hirabayashi et al., 2021; Bernhofen et al., 2021; Jongman et al., 2012), the exposure of populations inhabiting or neighboring wetlands has proved to be difficult to quantify. This reflects the difficulty of flood modelling in complex, low-lying, and highly vegetated landscapes (Trigg et al., 2016) and may also reflect the low wealth of wetland populations, which means that they have not been a priority for flood modelling by the insurance sector. In low-income regions of the world such as South Sudan where water infrastructures are limited or non-existent, flooding is a key threat facing communities. This study focuses on the Sudd, a term derived from the Arabic word, sadd (سد) which means barrier or obstruction. In the Sudd region, local communities have always had to cope with flooding and have adopted practices that benefit from the proximity to water (e.g., for livestock watering) whilst seeking to inhabit less exposed locations. However, geomorphological processes, poverty, changing cultural practices (e.g., swift shifts from nomadic lifestyles to more fixed habitations), and the disruption of the development of social and economic fabric of the societies through successive wars (1983-2005; 2013-2018) exacerbate communities' exposure and vulnerability to flooding.

Given the changing complex hydrology, limited hydrological observations, and weak local expertise due to decades of conflict, there is no large-scale local modelling of flooding processes in the Sudd region. This study therefore makes use of global flood modelling outputs, comparing them with one another, with gauged data and with satellite flood observations to evaluate their accuracy. These flood predictions are intersected with a range of recently released global georeferenced population products to estimate the population exposed to flooding in and

around the perimeter of the floodplains of the Sudd. The results from this study demonstrate the global significance of model intercomparison as best practice for any flood exposure analysis to underpin policy and decision-making in Africa and other data-scarce regions.

4.2 Study area

4.2.1 Hydrology

The Sudd is the largest tropical wetland in the world, covering a vast area of approximately 57,000 km² - 90,000 km² (Nile Basin Initiative, 2020a) and situated in South Sudan in the lower reaches of Bahr el Jebel/White Nile at an elevation of 380-450m above mean sea level. All streamflow from the upper catchments, including mountain spring water in the African Great Lakes region and western highland of Ethiopia drain into the Sudd (Figure 5), thereby enabling the thriving aquatic ecosystem and supporting the largest mammal migration in the world (African Parks, 2024). The “Spade-like-Shape” of South Sudan, with a depression in the center of the country, is an accumulation conveyor for flood waters, making the Sudd a key part of the Nile River system that maintains steady flow year-round.

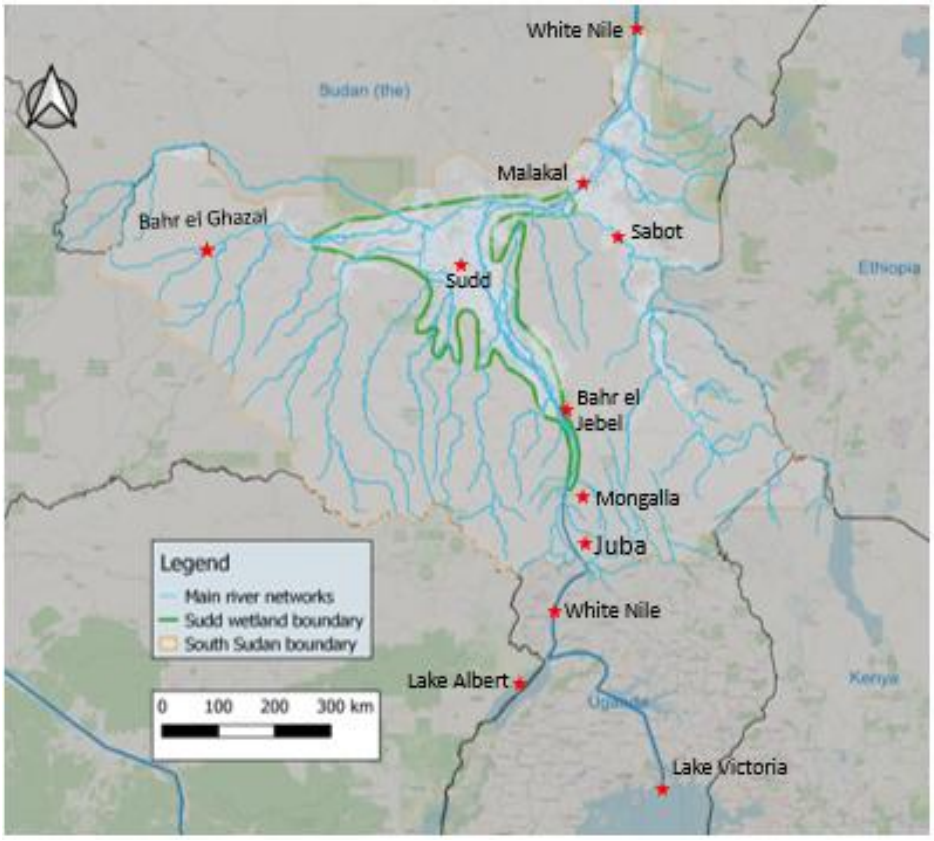


Figure 5: The Sudd region. The figure depicts the White Nile from the Equatorial Lakes region and through South Sudan; the Bahr el Jebel Basin; the Sudd entrance at Mongalla ; the Sudd exit at Malakal; the Bahr el Ghazal Basin; and the Sobat Basin.

The Sudd ecosystem services provide millions of people with livelihoods but also cause flooding in the Sudd region. The outflow from the equatorial lakes leads to strong seasonal inundation, characterized by annual flood pulses (Rebelo et al., 2012), which is further modified by local precipitation and evaporation (Mohamed and Savenije, 2014), leading to highly complex and seasonal behavior (Sosnowski et al., 2016). The wetland area is a shallow depression, sloping gently to the north with a gradient of 1.0-1.5cm/km (Nile Basin Initiative, 2020). The Sudd extent varies from season to season, inter-annually, and over decades. Due to increased rainfall in the African Great Lakes region from 1961 to 1964, severe flooding occurred in the Sudd region and the Sudd extent increased by 300% (Nile Basin Initiative,

2020;Gowdy and Lang, 2016). However, from 1965 to 1978 the Sudd extent decreased by 47% due to prolonged drought (Lambert, 2009; UNEP, 1997).

Previous researchers have adopted different boundaries for the study of the Sudd wetland. These sizes range from relatively small areas of 8,000 km^2 to large areas of 100,000 km^2. These varying estimates of the Sudd extent demonstrate high levels of intra- and inter-annual hydrological variability and the overall lack of standardized and long-term monitoring data on the extent of water bodies. This can be increasingly addressed through satellite products (Borgomeo et al., 2023); Peterson et al., 2024) that provide wide spatial coverage, near real-time data acquisition, ability to monitor remote areas, penetration through cloud cover and detailed mapping of flood extent. The consensus for the Sudd extent is in the range 57,000 km^2 to 90,000 km^2, which is supported by several literature sources (Figure 6) including UNESCO's designation of an area of 57,000 km^2 of the Sudd as a Ramsar Wetland (UNESCO World Heritage Convention, 2006). However, this range in the Sudd extent is surpassed during extreme flooding such as in the 1960-1964 and 2019-2022 flood events.

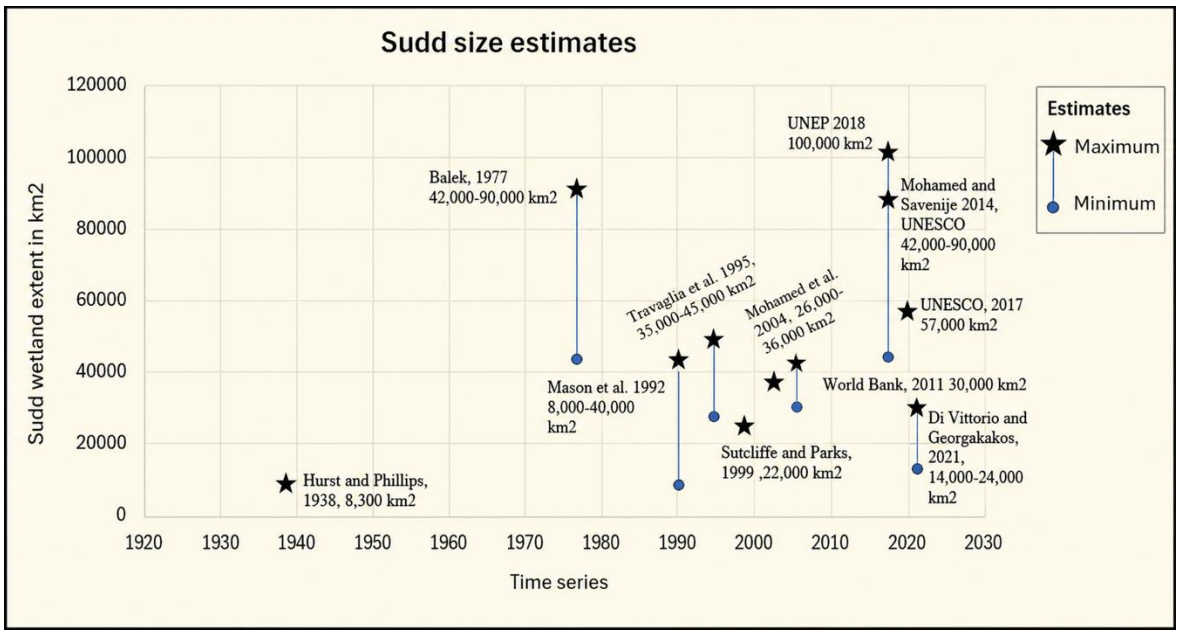


Figure 6: The Sudd wetland: varying estimates of the Sudd size.

Some of the previous works (Figure 6) including Balek (1977), Mohamed and Savenije (2014), Tootchi et al. (2019), World Bank (2011), and UNEP (2018) have not specified measurement methods that were used to determine the size of the Sudd. However, several other authors (Figure 6) have used various measurement methods to derive the Sudd sizes. These methods include water balance and aerial surveys (Hurst and Phillips, 1938), remote sensing (Mason et al., 1992), surveys remote sensing (Travaglia et al., 1995), water balance model (Sutcliffe and Parks, 1999), remote sensing (Mohamed et al., 2004), regional climate model (Mohamed et al., 2005), and remote sensing (Di Vittorio and Georgakakos, 2021).

Evapotranspiration exceeds precipitation during nine months of the annual cycle, hence direct rainfall over the Sudd is a minor contributor to the water balance of the Sudd (Mohamed & Savenije, 2014). The Sudd wetland (Figure 7) hydrology and water balance are mainly influenced by precipitation variations upstream of the Sudd and changing water levels of the Lakes Victoria, Kyoga, George, Edward, and Albert (Mohamed and Savenije, 2014; Mohamed,

2021; Howell, 1983; Howell et al., 1988; Sutcliffe and Parks, 1999). An estimated 75 % of inflow water originates from the equatorial lakes and 25 % comes from torrents between Lake Albert and Mongalla (Mohamed and Savenije, 2014; Birkett et al., 1999; Nicholson, 2017; Nicholson and Yin, 2001).

Historical accounts (Figure 7) report five major floods in some parts of the Sudd region in the nineteenth century: 1820-5, 1878, 1894, 1895, and 1896 floods. The 1820s flood lasted about five years, resulting in significant deaths, destruction of livelihoods, and long-term displacement and migration of the communities (Johnson, 1992; Johnson and Anderson, 2019). In the twentieth century, communities in the Sudd region were devastated by major floods in 1916-17, 1931, 1932, 1944, 1961-64, 1989-91, and 1991 (Johnson, 1992). These past extreme flood events reportedly caused destruction of properties and human suffering. Lately, floods of this magnitude devastated South Sudan in 2019-2022, inundating four of the ten states that are predominantly in the Sudd region floodplains.

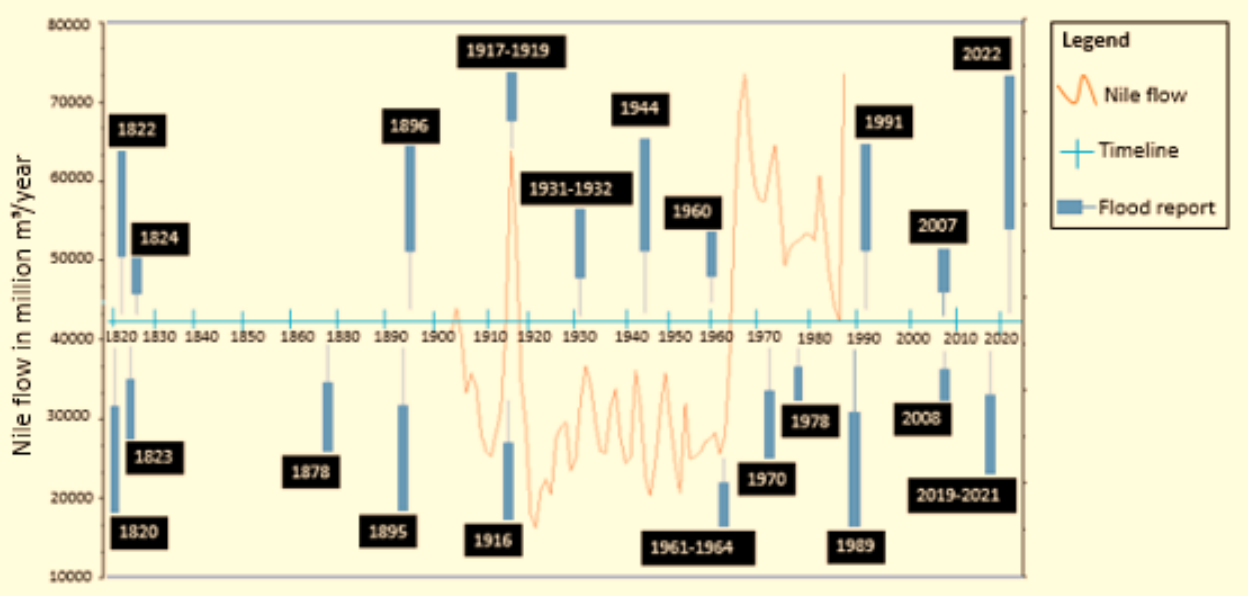


Figure 7: The Sudd major flood timeline. This figure depicts years in which major flood events were reported (Johnson, 1992) and gauged Nile flow (orange graphic line) from the equatorial lakes into the Sudd at Mongalla station (Egypt Nile Control Department, 1933).

Those major flooding events caused highly disruptive impacts to former Bor- Duk District (now, Duk county, Twic East County, and Bor County) in Jonglei State, major parts of Ayod, Old Fangak and Nyirol counties in Jonglei State, and Khor Atar (now, a county) in Jonglei State.

During the period of 1905-1983, discharge peaks from the equatorial lakes of over 30 billion m^3/year (Figure 7) at Mongalla (Figure 5) tend to be associated with flood occurrence reports in the Sudd region. This linkage is further evidenced by stream inflow, and runoff increases during 2019-2022 that raised the water level in Lake Victoria by 13.42 meters above sea level in May 2020, surpassing the 13.41-meter, the previous highest recorded water mark in 1964 (Lake Victoria Basin Commission, 2020). The resultant substantial inflow into the Sudd caused dramatic flooding in South Sudan during the same period. The cumulative impacts of these flood events include population displacement, ecosystem degradation, and inter-communal conflicts over access to a few dry islands within the Sudd and limited water and environmental resources.

4.2.2 People and population

The Sudd supports different ethnic groups who temporarily migrate during the wet-dry interseason to make use of the services the Sudd ecosystem provides(Rebelo et al., 2012). Gowdy and Lang (2016) found most of the local people of the Sudd region are Nilotic speaking people (Dinka, Nuer, Shilluk, Luwo, Mundari, Jale, Maban, Anuak, and Murle) who are agro-pastoralists (Howell, 1983; Howell et al., 1988; Evans-Pritchard, 1940) that have adapted their

economies and cultures to the demands of the hydrological cycles of the Nile. These nomadic local communities rely on the seasonal flooding to recharge soil moisture and regenerate the grasslands that support their cattle, their primary source of food and income (Howell et al., 1988; Di Vittorio and Georgakakos, 2021). Most of the local populations move from their permanent settlements on the highlands to grazing in the intermediate lands (toich/swamps) at the beginning of the dry season and return to the highlands in May-June when the rainy season starts (Gowdy and Lang, 2016). The wetland flooding regime has defined the livelihoods of millions of people who live in the Sudd region.

South Sudan's population estimates are uncertain. The country has not conducted population and housing census since its independence from Sudan in 2011. As it was an autonomous region within Sudan, South Sudan's last population and housing census was conducted in 2008 as part of the 2005 Comprehensive Peace Agreement (CPA) that ended the 21-year long war between Southern Sudan region (now South Sudan) and the Government of Sudan. (See supplementary materials for analysis of challenges of population counts in South Sudan). In all these works, no specific population estimate was provided for the Sudd wetland region, but UNESCO (2017) estimated that one million people inhabit the Sudd wetland region. This estimate is low compared to extrapolations of population based on estimates from the 2008 Census for the states or counties that are predominantly in the Sudd region, which would suggest three to five million people currently reside in the Sudd region. These discrepancies justify a more comprehensive assessment of the affected population in this vulnerable region.

4.3 Data and methods

The study used five global data sets of flood hazard, four global data sets of human population, satellite-derived Earth observation inundation extent, and gauged discharge into the Sudd at Mongalla to analyze flood hazards and population exposure in the Sudd region. The workflow for integrating flood extent data with population datasets to estimate population exposure in the Sudd region is provided in Supplementary Information (Figure 17). Flood exposures were calculated primarily for the permanent and seasonally flooded Sudd, including the western and eastern floodplains of the Sudd wetland. Flood exposures were also calculated for South Sudan at the national level, state level, and administrative areas. Principally, the states of Unity, Jonglei, Upper Nile, and Lakes as well as parts of Central Equatoria, Eastern Equatoria, Western Equatoria, and Warrap fall in the Sudd region.

4.3.1 Global flood model intercomparison

The Global Flood Models (GFMs) compared in this study are summarized in Table 4. The flood maps associated with the GFMs are typically presented with flood extent and/or depth at a given return period across the modeled domain (Bernhofen et al., 2022). These models were chosen because they were the only available models that provided hazard maps- at the time of research- in data-poor region of South Sudan. The outputs of the native flood hazard map of each GFM were acquired between January and July 2023. The outputs from Aqueduct, JRC, and CIMA-UNEP were obtained from open access databases. Respective developers provided the Fathom Global and CaMa-UT flood maps. Previous researchers including Bernhofen et al. (2022)

compared these products in five countries at national scale; Trigg et al. (2016) assessed credibility of these products for African fluvial flood risks analysis; and Aerts et al. (2020) compared these products for flood hazard and exposed GDP in China as a case study.

Table 4: Global Flood Models (GFMs) used in this study [adapted from Trigg et al. (2016)].

Model Description	JRC Global	GLOFRIS Aqueduct	CIMA-UNEP GAR 2015	Fathom 2.0 Global	CaMa-UT 4.04
Model type	Cascade	Cascade	Gauged flow	Gauged flow	Cascade
Global Climate Dataset/ Global Gauge Dataset.	ERA-Interim climate forcing dataset from 1980 to 2013.	EU-WATCH global climate forcing dataset from ERA-40 reanalysis dataset, 1980 to 2015.	EC-Earth and GRDC Global dataset of river discharge, 9500 stations record from 1960 to 2012, and 1981-2012	GRDC and USGS Global dataset of river discharge 9500 stations; record from 1983 to 2002 and 1807-2009.	JRA-25 global climate forcing reanalysis dataset from 1979 to 2010.
Land Surface Model	HTESSEL Global Hydrological	The PCR-GLOBWB model.	Continuum Global Hydrological model.	Flood hydrographs force	MATSIRO-GW Global Hydrological Model (GHM).

	Model (GHM).			hydrodynamic simulations.	
River Routing Model	LISFLOOD-Global groundwater and river routing model.	Dynrout Extension of PCR-GLOBWB model.	Hydraulic flood model (global river routing).	LISFLOOD-FP global river routing model.	CaMa-Flood (version 4.04) model.
Flood Frequency Analysis	Annual maxima discharge; Gumbel distribution estimates discharge for a given return period.	Annual maxima flood volumes: Gumbel distribution is fitted for a given return period.	Index flood method computes extreme discharge values; regression techniques on geomorphological and climatological variables.	A hybrid-clustering approach in conjunction with a flood-index methodology.	Annual max water level (0.25-degree grid box) unit catchment; Gumbel distribution estimates peak water level for a given return period.
Downscaling Method	Spread over "flood points" that	GLOFRIS downscaling module, into	No downscaling.	No downscaling.	Downscaling from 0.25°

	are regularly spaced 10 km apart along the 30 arc seconds river network.	high resolution (30 arc seconds or ~1km) hazard maps.			preserving water volume.
Geographical Datasets	HydroSHEDS DEM and Drain Direction map.	HydroSHEDS derived SRTM30 DEM and river network.	A reconditioned SRTM3 (version 4.12) DEM and HydroSHEDS river network.	MERIT HydroSHEDS.	MERIT-HydroSHEDS
Return Period (years)	Fluvial flood 10, 20, 50, 100, 200, 500, 1000 .	Fluvial flood 5, 10, 25, 50, 100, 250, 500, 1000.	Fluvial flood 25, 50, 100, 200, 500, 1000.	Fluvial/Pluvial 5, 10, 20, 25, 50, 75, 100, 200, 250, 500, 1000.	Fluvial 5, 10, 20, 25, 50, 100, 200, 250, 500, 1000.
Modelled Resolution	0.1°	5 arcmin.	32arcsec.	3°	0.25°
Output Resolution	30arcsec.	30arcsec.	32arcsec.	3arcsec.	Arcsec.

Reference	https://data.jrc.ec.europa.eu/collection/id-0054.	https://www.wri.org/aqueduct.	https://www.preventionweb.net/english/hyogo/gar/2015/en/home/data.html.	https://www.fathom.global/product/flood-hazard-data-maps/.	http://hydro.iis.utokyo.ac.jp/~yamadai/cama-flood/index.html.

The GFMs use different Digital Elevation Models (DEMs). FATHOM and CaMa-Flood v4 both use the Multi-Error-Removed Improved-Terrain DEM (MERIT DEM), which is a significant improvement as it "separates absolute bias, stripe noise, speckle noise and tree height bias using multiple satellite data sets and filtering techniques" to improve on the SRTM baseline (Yamazaki et al., 2017; Hirabayashi et al., 2021).

There are two different modelling approaches, the cascade model structure (CaMa-UT, GLOFRIS, and JRC) and the gauged-flow model structure (Fathom and CIMA-UNEP) (Trigg et al., 2016; Aerts et al., 2020). A detailed description of the cascade model structure is provided by Winsemius et al. (2013) and for the gauged-flow model structure by Sampson et al. (2015). The cascade model structure uses global climate reanalysis data, driving a land surface model to produce flows at locations along a river. The gauged-flow model structure uses gauged-discharge or gauged-precipitation datasets from over 9500 stations as input.

The modelling approaches differ between using regionalization techniques that depend on 180 upstream catchment characteristics (Fathom) and models that need to be complemented by hydrologic simulations (CIMA-UNEP)(Aerts et al., 2020). The gauge models use a growth curve to determine extreme flow that is then input into a hydraulic model that predicts the flood

extent and depth for a given return period flow (Trigg et al., 2016). Depending on the GFM model type, the climate model used, or the gauge data used, each GFM will have a different estimated return period extent (Bernhofen et al., 2021).

All the model outputs were converted to a binary flood (depth > 0 m), dry (depth = 0 m) raster for the computations for this study. Exposure analysis was derived by intersecting the flooded areas with spatially distributed exposure datasets for four gridded population products. Summary statistics of inundated areas and population exposure for areas of interests were computed for the Sudd region, South Sudan, and the ten states.

To evaluate model agreement, the study aggregates the wet area extent from the 100-year return flood extents from all five models to develop categories that indicate how many models agree that an area is flooded. This produces a single dataset with a category as an integer that indicates the number of models that agree. This aggregation was conducted at the finest resolution across all the models to ascertain consistency and accuracy. A model agreement index (MAI) (Equation 1) is then calculated from these categories for a given region (South Sudan country level and the Sudd region) by summing up the total area of each flooded category, multiplied by the fraction of models that agree in that category, and then dividing this sum by the maximum possible model agreement, resulting in a fraction of model agreement (Trigg et al., 2016)

$$\mathrm{MAI} = \frac{\sum_{i=2}^{N} \frac{i}{N} a_i}{AN}, \qquad (1)$$

MAI = Where: A is total flooded area predicted by all models, a_i is the flooded area for an aggregated category, N is the number of models in comparison, and i is the aggregated category

(i.e., number of models in agreement). The index does not assume any single model is more correct than the rest and is solely based on an agreement measure for wet areas only.

4.3.2 Satellite observations: Sudd flooding extent

The study employed a satellite remote-sensed method to determine the maximum annual flooding extent in the Sudd study region for 2000 to 2022. This method uses the Moderate Resolution Imaging Spectrometer (MODIS) land surface temperature (LST) product (MOD11A1). MODIS LST from 2000 to 2022 was processed using Google Earth Engine. A pixel-based quality control mask was applied to remove pixels impacted by clouds, cloud shadows, high aerosols, and band saturation, and all remaining values were converted to degrees Celsius. All available data was aggregated for each month, and the median was calculated to obtain a complete image that is representative of the full month. Histograms of each monthly image were then created and showed a bi-modal distribution; lower values are assumed to be inundated pixels, and higher values are assumed to be dry pixels. The temperature that provided the best split between the distributions (identified by the minimum frequency) was selected as a threshold value for each month that could be used to delineate the flooded and non-flooded areas. The thresholds values were applied to create monthly binary flood (inundated or dry) maps as raster flood maps at 0.1 degree by 0.1-degree grid resolution. MODIS LST has been used to map wetland extents (Ordoyne and Friedl, 2008) and rice paddies (Zhang et al., 2017) and can effectively delineate flooded area boundaries during dry, hot periods because inundated areas are often much cooler. MODIS LST data in the Sudd region shows high contrast between the wetland area and dry land during the dry season, generally from November to February (Di

Vittorio and Georgakakos, 2021). Fortunately, the dry season aligns with the period when the Sudd reaches its max extent, thus according to several studies (Sutcliffe and Parks, 1999; Rebelo et al., 2012; Di Vittorio and Georgakakos, 2018) can be leveraged to delineate the annual maximum flooding extent.

4.3.3 Population exposure to flood hazards

Given the challenges in estimating the population and households of South Sudan, and for the Sudd region, the study makes use of global georeferenced population products from open access sources as an alternative approach to estimate South Sudan populations and map spatial distribution. These gridded population products (Table 5) combine census data with remote sensing data to estimate where people live.

Table 5: Characteristics of georeferenced global population datasets [adapted from POPGRID Data Collaborative (2023)].

	GPWV4	GHSL-Pop	LandScan	WorldPop
Population data	2010 Population and Housing Censuses.	GPWv4.10 data.	Subnational census and administrative data.	GPWv4 census data.

Geospatial ancillary inputs	Protected areas and water bodies.	Built-up areas mapped in the Global Human Settlement Layer Built Up Extent (GHSL-BUILT).	Roads, land cover, built structures, cities or urban areas, infrastructure, environmental data, protected areas, and water bodies.	Roads, land cover, built structures, cities or urban areas, nighttime lights, infrastructure, environmental data, protected areas, and water bodies.
Satellite imagery	None.	Landsat imagery for 1975, 1990, 2000, 2014.	Maxar (formerly DigitalGlobe).	Landsat Enhanced Thematic Mapper (ETM), Landsat, TerraSAR-X, TanDEM-X,

				DMSP and VIIRS..
Source of data adjustment	Official country totals for censuses and UNPD estimates.	UNPD estimates..	US Census Bureau International Programs estimates.	Country-official estimates and UNPD estimations.
Method	Areal Weighting.	Binary dasymetric mapping.	Multi-variable dasymetric.	Random forest.
Epoch	2000, 2005, 2010, 2015, and 2020.	1975, 1990, 2000 and 2015.	Annual since 1998.	2000-2020.
Resolution	30 arc-seconds (1 km)	250 m, 1 km (World Mollweide) 9 arc-seconds, 30 arc-seconds (WGS84).	30 arc-seconds (1 km).	3 arc-second (100 m).
Data access	https://www.earthdata.nasa.gov/data/projects/gpw.	https://human-settlement.emergency.copernic	https://landscan.ornl.gov/.	https://www.worldpop.org/.

		us.eu/ghs_pop2022.php.		

All the population datasets were resampled and projected to the same resolution for this study. To ensure consistency among the population products compared, this study only used the most up-to-date epoch for each population dataset, and the single most recent year, 2020. The extended data documentation is available through the POPGRID website (https://www.popgrid.org/, last access: June 2023). Recent works by Smith et al. (2019) and Bernhofen et al. (2021) found that flood exposure estimates are significantly impacted by the population datasets used. The methods for these global population products, their development, and their wide-ranging applications are reviewed in detail by Leyk et al. (2019). In summary, there is not one single product that is systematically more appropriate than the rest.

The GPW approach evenly redistributes source data into target grid cells based on proportions of overlap with no ancillary data input informing the process (Goodchild and Lam, 1980; Baynes et al., 2022). This assumption (Leyk et al. 2019) is a gross simplification since population distributions are not uniform. The GHSL-Pop approach is grounded on the concept that buildings and their agglomerations (i.e., settlements) are nowadays the main visible and direct manifestation of human presence and activity on the Earth's surface (Leyk et al., 2019; Bernhofen et al., 2021). A limitation associated with GHSL-Pop is its sole use of built-up mapping as detected from satellite imagery, which may miss settlements units that are too small to detect in the rural areas such as the Sudd region.

In comparison, WorldPop and LandScan use similar geospatial ancillary inputs (Table 5), except that the former additionally correlates nighttime light with population distribution. However, nighttime lights are sensitive to the level of economic development given some areas such as urban centers and airports exhibit high values despite levels of residential occupancy. A shortcoming of the nighttime light technique is its inability to capture some of the scattered rural settlements and populations in the rural areas around the Sudd and within its islands without electrification.

LandScan may perform well in capturing urban population distribution but is less reliable in rural areas (Aubrecht et al., 2016), as satellite imagery may fail to detect certain settlements that are constructed with materials from the grasslands or woody vegetation. WorldPop uses machine learning to identify significant relationships from the input census data and apportions some population to rural areas under the assumption that not all "built-up" areas will be picked up in the satellite imagery. Despite this advantage, among others, the WorldPop model has been criticized for excluding more uninhabited land than do the other datasets due to its clustered populations (Aubrecht et al., 2016).

4.4 Results and discussion

4.4.1 Global flood models agreement

This section compares flood hazard extents simulated under different return periods by global flood models (GFMs) to characterize flood hazard in the Sudd region. In this chapter, flood probabilities refer to annual exceedance probabilities (AEPs) associated with specific flood return periods. Thus, a 1% probability flood event refers to a 1% AEP flood, equivalent to a 100-year return period flood scenario. Similarly, 2%, 4%, and 5% probability flood events correspond approximately to 50-year, 25-year, and 20-year return period scenarios, respectively. These probabilities describe the likelihood of a flood magnitude being equaled or exceeded in any given year based on the statistical assumptions of each global flood model, rather than the probability that a particular location will flood in that year. The flood depth was used to compare the range of flood depth across the five different global flood products. Flood depth was used to compare differences in inundation magnitude among the five global flood products. Both CaMa-UT and JRC modelled the largest hazard extent and greater flood depths under the **1**% annual exceedance probability (AEP), equivalent to a 100-year return period flood scenario (Figure 8)**,** while differences among models were also examined under the 4% and 5% AEP scenarios in the detailed inset area (Figure 9).

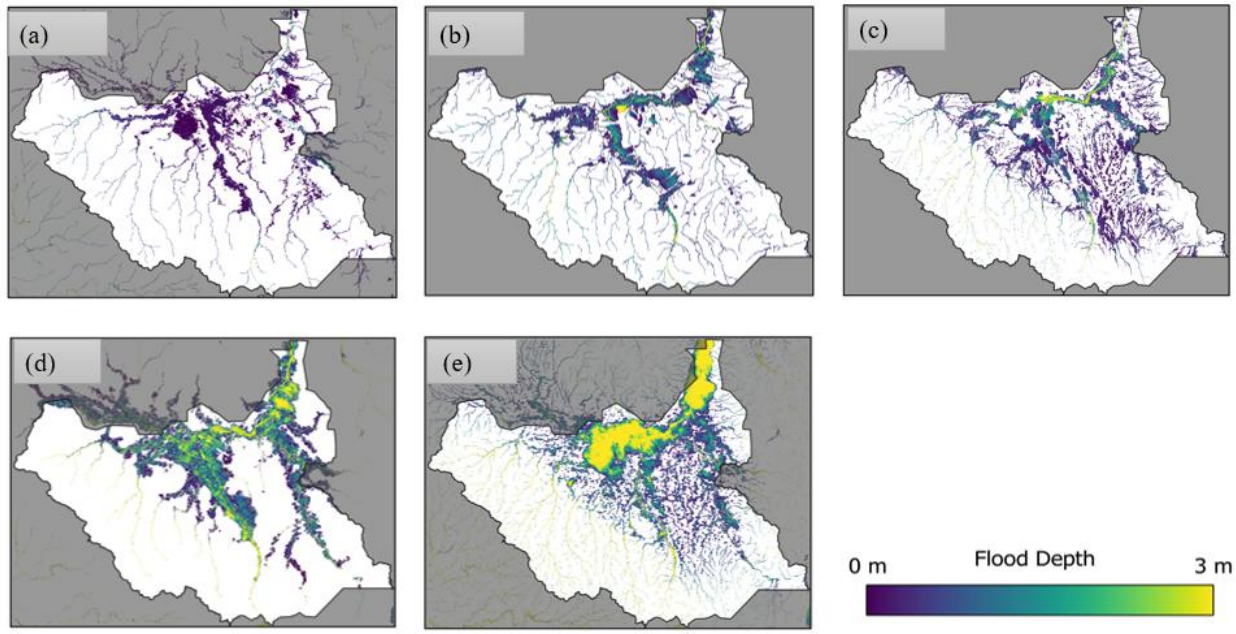


Figure 8: Comparison of simulated flood extent and depth under a 1% annual exceedance probability (100-year return period) flood scenario among five GFMs: (a) Aqueduct, (b) CIMA-UNEP/GAR2015, (c) Fathom Global, (d) JRC, and (e) CaMa-UT.

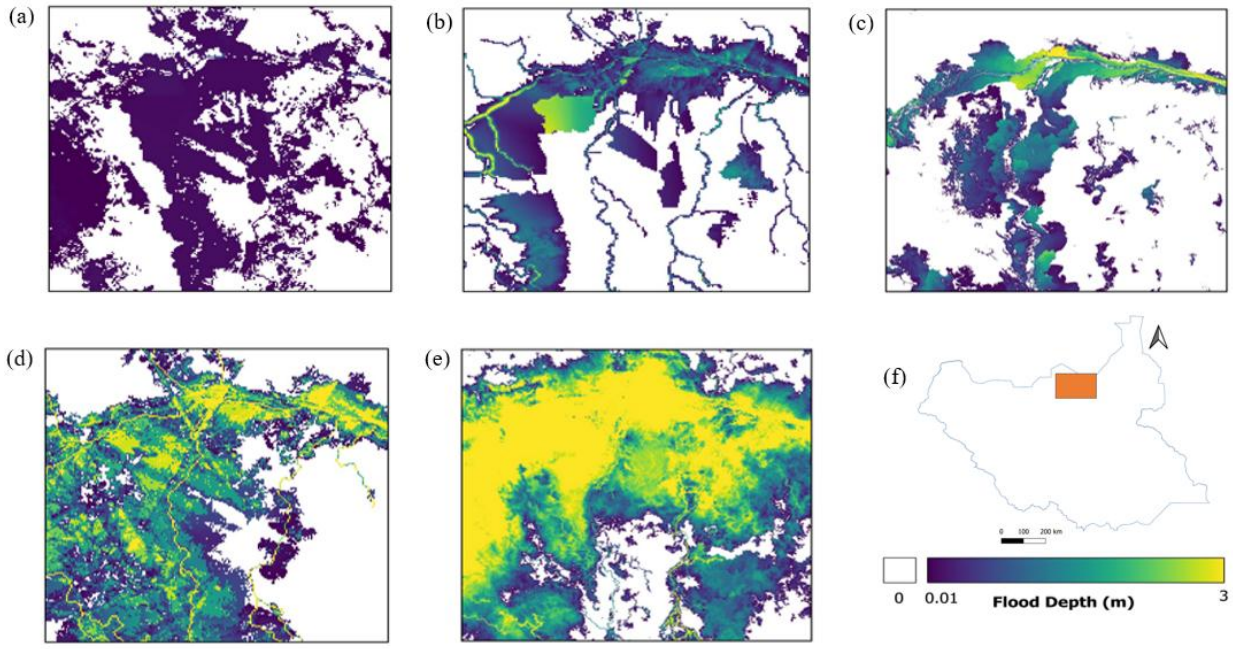


Figure 9: Comparison of detailed flood hazard extents simulated by five global flood models (GFMs) under 4% and 5% annual exceedance probability (AEP) flood scenarios (approximately 25-year and 20-year return periods, respectively): (a) Aqueduct, (b) CIMA-UNEP/GAR2015, (c) Fathom Global, (d) JRC, and (e) CaMa-UT. Panel (f) shows the inset area within the Sudd region of South Sudan.

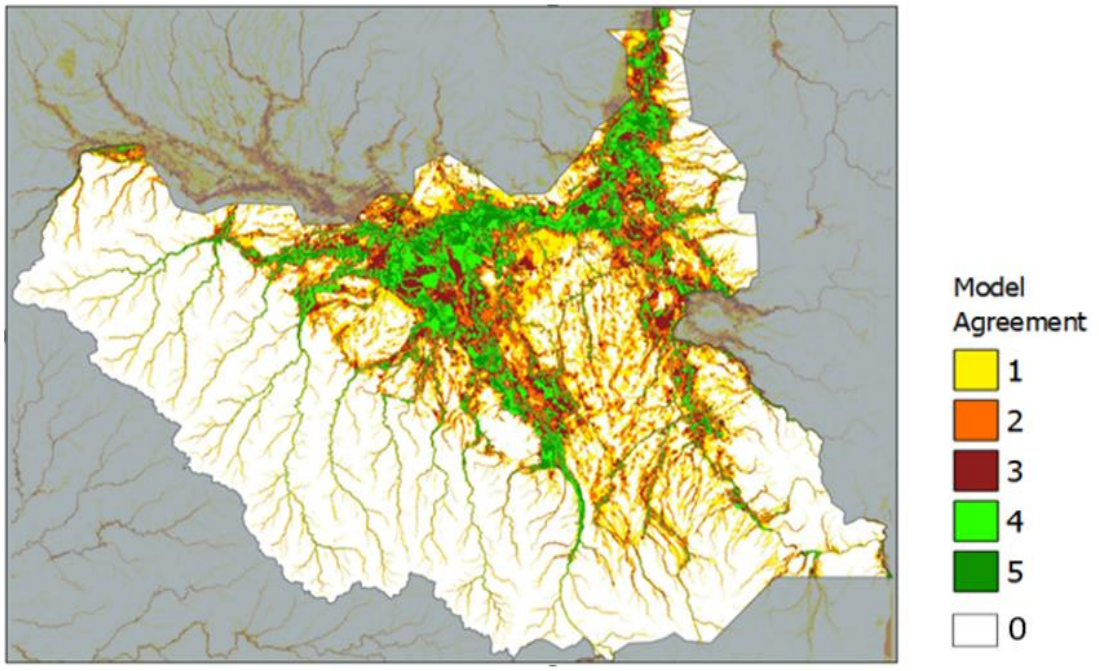


Figure 10: Figure 10: Model agreement of simulated spatial flood extent under a 1% annual exceedance probability (100-year return period) flood scenario among five GFMs. Aqueduct, CIMA-UNEP, Fathom Global, JRC, and CaMa-UT; 0 corresponds to dry area- no model predicting flooding, whilst 1 to 5 indicate the number of models in agreement.

As can be observed, aggregated results (Figure 10) show agreement is higher in the narrow-confined floodplains near the confluences of Bahr el Ghazal, Bahr el Jebel, and Pibor-Baro-Akobo-Sobat systems (dark and bright green colors). Agreement is however least along the peripheral areas of the floodplains and drier areas. Disagreement is also visible in the central area of the Sudd (i.e. between Leer and Bentiu in Unity State, and around the confluence of Sobat and the White Nile in Upper Nile State).

Some disagreement can be attributed to different size rivers that these rivers model. Some models are configured to simulate only major rivers while others incorporate smaller tributaries. For example, Bernhofen et al. (2021) found that in South Sudan the exposure was ~4 x more

when you consider smaller rivers (>50 km^2 upstream drainage area) compared to when you only look at major rivers (> 5000 km^2 upstream drainage area).

The differing approaches to global flood hazard mapping result in flood extent disagreement (Aerts et al., 2020; Trigg et al., 2016) and varied performance (Bernhofen et al., 2018), suggesting no single model is uniformly fit for a given purpose. Some of the previous intercomparison studies found large differences between these models in Africa (Trigg et al., 2016) and China (Aerts et al., 2020). An intercomparison study at the country level (Trigg et al., 2016) found high exposure for South Sudan and more agreement between models as all identify the large Sudd wetlands. However, Trigg et al. (2016) also found some disagreement as dynamics of vegetation and evaporation play a dominant role in the Sudd flood extent, and not all models include these processes. Although return-period flood metrics are widely used in global flood hazard modelling, their interpretation in the Sudd requires caution because flooding is governed not only by peak discharge events but also by seasonal water storage, floodplain connectivity, vegetation dynamics, and evapotranspiration processes.

Table 6: Flood scenarios represented by 4% and 5% annual exceedance probability (approximately 25-year and 20-year return periods).

Model	4% and 5% annual exceedance probability flood scenarios		
GFMs.	South Sudan (SSD) flood area extent (km^2).	Sudd Region flood area extent (km^2).	Sudd flood area as % of SSD flood Area.
Aqueduct-4%	78,774	67,783	86

CIMA-UNEP-4%	87,752	68,880	78
Fathom-5%	85,031	65,429	77
JRC-5%	129,772	116,876	90
CaMa-UT-4%	158,629	134,392	85
Model	2% annual exceedance probability flood scenarios		
Aqueduct	80,451	69,227	86
CIMA-UNEP	101,546	81,260	80
Fathom	113,027	88,692	78
JRC	139,012	127,805	92
CaMa-UT	165,797	143,838	87
Model	1% annual exceedance probability flood scenarios		
Aqueduct	82,158	706,80	86
CIMA-UNEP	104,835	84,059	80
Fathom	132,308	104,829	79
JRC	144,847	129,762	90
CaMa-UT	176,935	153,172	87

Besides Aqueduct, both the Fathom and CIMA-UNEP that belong to gauged-flow model structure have a comparably smaller percentage of total flooded areas in the Sudd region (Table 6). The uncertainty associated with the application of the gauged-flow models in the Sudd region could pose some challenges in flood hazard mapping and flood risk management. One such uncertainty which concerns the estimates of the flooded areas is that South Sudan gauge stations and data record are limited. The gauges along the Bahr el Jebel/White Nile and the

Sudd stopped working during the civil war from 1983 to 2005. There are only about four river gauge stations (Juba, Malakal, Renk, Wau, and Raga) that are operational in the country, but whose readings resumed intermittently only in 2007 after the CPA. The different performances by these gauged-flow models in the Sudd region are probably attributable to the absence or limited availability of gauge stations and historical record of gauge data. Comparably, the underpredicted flood hazards by these two methods could have implications on the utilization of flood exposure results and flood risk management.

4.4.2 Satellite observations: Sudd flooding extent

The maximum annual flood extent of the Sudd wetland system was estimated for the period 2000–2022 using satellite observations and is presented in Figure 11. The analysis focuses on the Sudd hydrological system, including the main Bahr el Jebel floodplain and connected parts of the Sobat floodplain, rather than the entire territory of South Sudan.

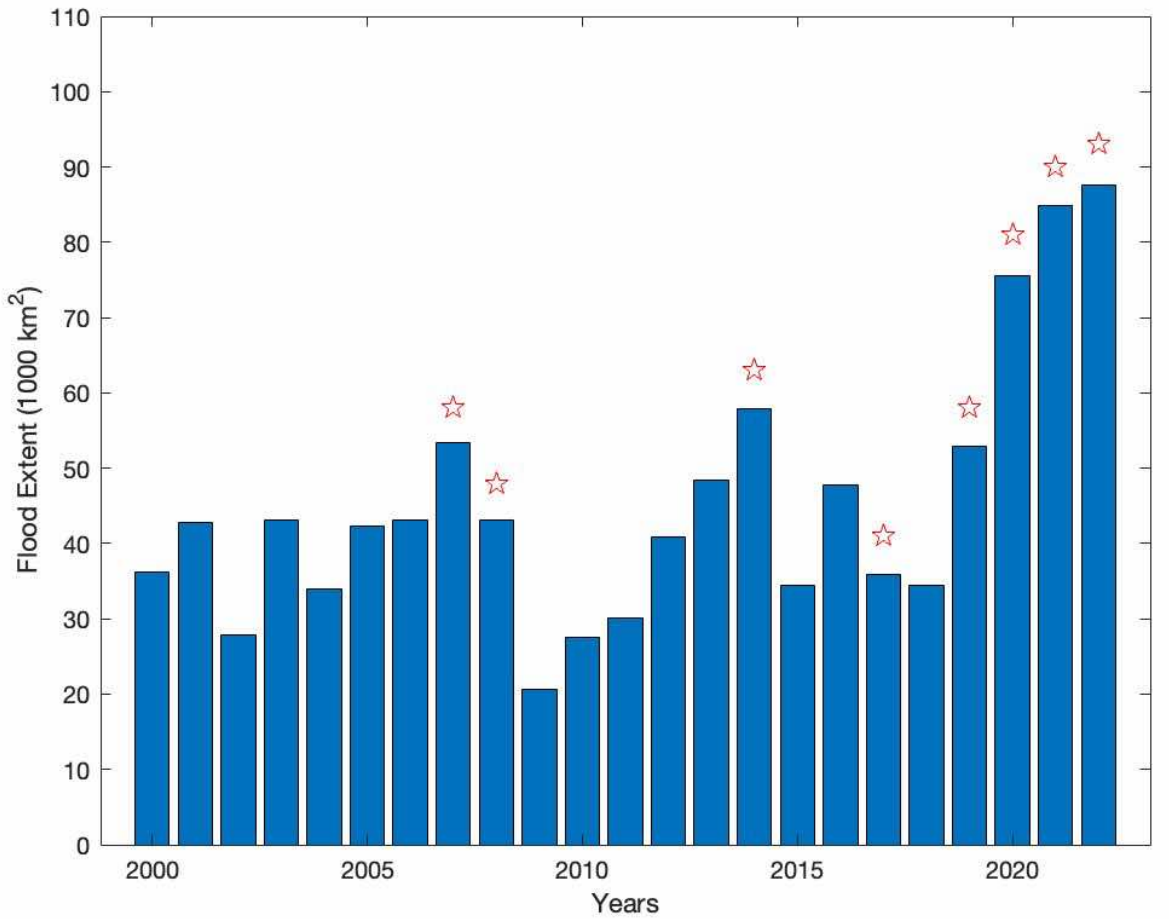


Figure 11: Sudd Maximum annual flood extent. The analysis represents the Sudd wetland and connected floodplain areas, including parts of the Bahr el Jebel and Sobat floodplains, rather than the entire area of South Sudan. Stars indicate reported major flood events (2007, 2008, 2014, 2017, and 2019–2022) corresponding to events shown in Figure 7.

During the 22-year period, five years (2009-2011, 2017 and 2018) were observed with comparatively less annual maximum flooded area, with 2009 exhibiting the least annual extent. A visual analysis of the 22 annual maximum flood extents within the Sudd hydrological system shows three distinct spatial regimes related to the connectivity between the major wetland components: 1) the Sudd/Bahr el Jebel basin to the central south, 2) the Bahr el Ghazal to the northwest, and 3) the Sobat to the northeast. Figure 12 depicts these three regimes, which are:

1) Isolated wetlands are shown with 2002 representing the regime that occurred in 15years: 2000, 2001, 2002, 2003, 2003, 2004, 2008, 2009, 2010, 2011, 2012, 2013, 2015, 2017, 2018, and 2019.
2) Connected wetlands: the Bahr el Ghazal and the Bahr el Jebel/Sudd connection is continuous in 2005, 2006, 2007,2014, 2016, and 2019. Figure 11 shows 2007 as the representative maximum flood extent. However, the connectivity of the Sobat, extreme northeast, to the Sudd is not part of this regime.
3) Merged wetlands: in 2020, 2021, and 2022 flood extents from the three basins, the Bahr el Ghazal, the Bahr el Jebel/Sudd, and the Sobat are merged. 2022 is representative of this regime illustrated in Figure 11.

In the 22-year period, the Bahr el Jebel, the Bahr el Ghazal, and the Sobat basins appear as separate water bodies until in the latest flood years (2021-2022) when they are hydrologically connected by flood water.

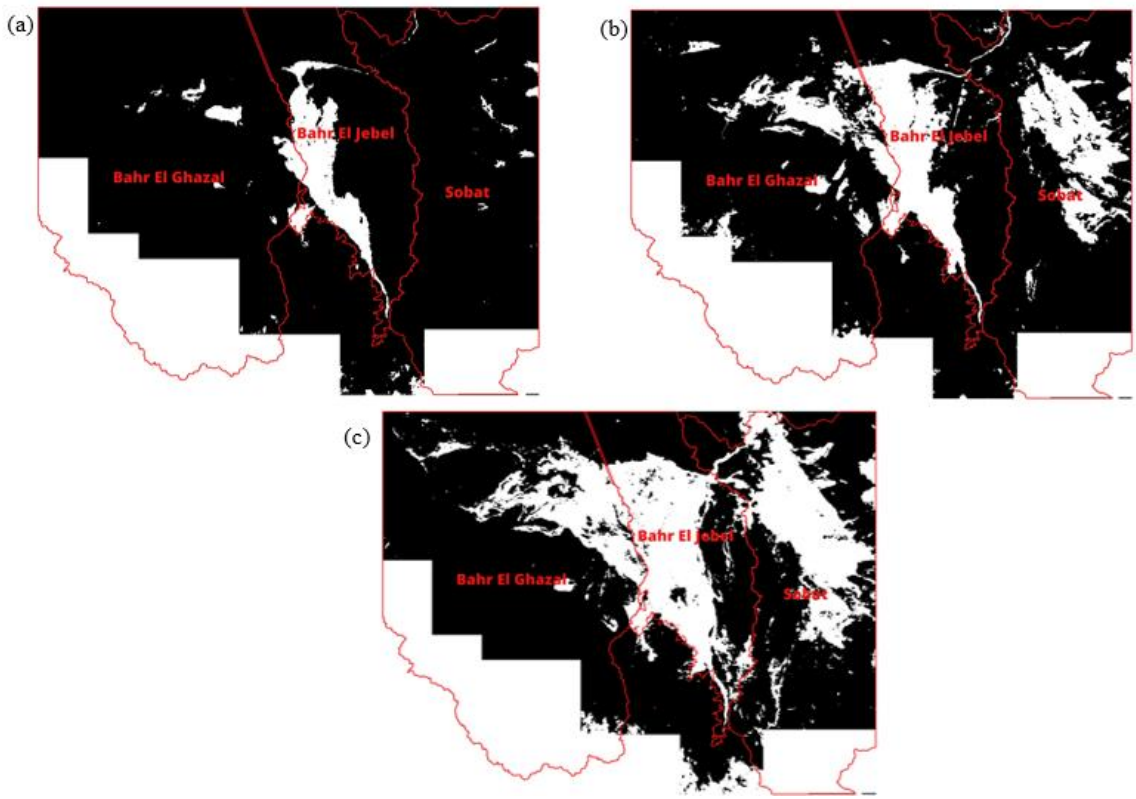


Figure 12: Satellite observation: Sudd annual maximum flood extent: (a) Isolated regime: representative year 2002 flood extent area (28,000 km2) - Bahr el Ghazal to the northwest, the Bahr el Jebel to the southcentral, and the Sobat to the extreme northeast are isolated; (b) Connected regime: representative year 2007 flood extent area (53,000 km2) – the Bahr el Jebel and Bahr el Ghazal are connected; and (c) Merged regime: representative year 2022 flood extent area (88,000km2) - the Sudd/Bahr el Jebel, the Bahr el Ghazal, and the Sobat are all merged.

The direction of the connecting flow is not clear, even in years (2020-2022) with apparent continuous connection between the three basins. The Bahr el Ghazal and the Sobat are augmenting flows to the Sudd. This is a point of uncertainty that previous researchers (Sutcliffe and Brown, 2018; Sutcliffe et al., 1999;) have identified, but which has not yet been settled. Looking at far eastern side of the flood maps, a substantial extent of the Sobat basin is observed in some years (2019-2022) that could be amplifying flooding in the Sudd in those years. The Sobat flows may have already filled up the channel capacity at the exit into the White Nile, causing a backwater effect toward the Sudd exit.

The dramatic increase in the flooded area from 2019-2022 (Figures 11 and 12) indicates a major change in the Sudd, signaling a whole new flow regime may be taking shape since 2019, with greater amount of water flowing to the Sudd from the equatorial lakes region, coupled with increased flow from the Bahr el Ghazal and the Sobat basins. The analysis highlights the high spatial and temporal variability of flood extents and flow regimes in the Sudd region. Understanding this complex change and its hydro-ecological implications for the welfare of the populations in the Sudd region is critical for understanding population exposure to flood risks. The study also computed the likelihood of flooding in the Sudd region. Figure 13 depicts a percentage probability that each pixel is flooded over the 22-year period of satellite observations.

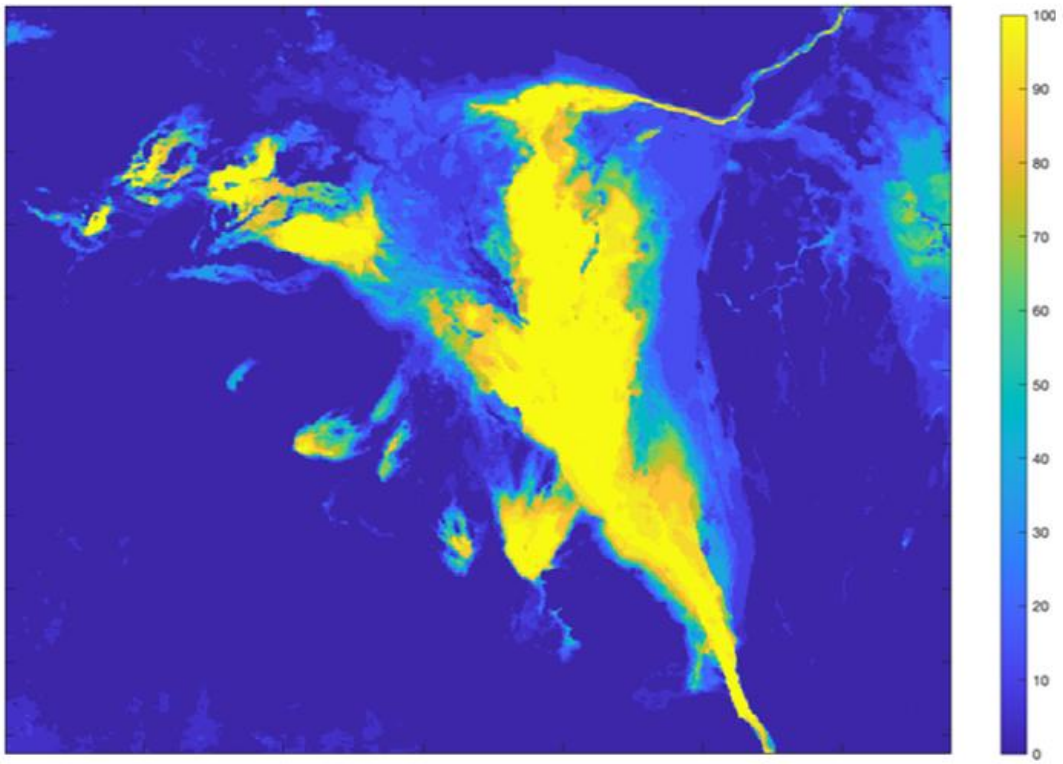


Figure 13: The percentage of years over 22 years that each pixel is flooded. The areas that are flooded in 90-100 % of the annual maximum extent images (yellow) can be considered the Sudd permanent wetlands and major tributaries; the orange area (80-90 %) appears to be a buffer area along the edge of the permanent wetland. The green areas (50-70 %) appear to be the seasonal wetlands that bridge the permanent wetland and the floodplains (30-40 %, light blue).

4.4.3 Comparison of satellite observations and GFMs results

To compare global flood model (GFM) simulations with historical satellite-derived observations, this study estimated the recurrence intervals of maximum annual flood extent from 22 years of satellite-derived flood extent estimates. A statistical analysis was conducted by fitting the 22 annual maximum flood extent observations to a generalized extreme value (GEV) distribution. The return levels derived from the fitted GEV distribution for 10-year to 100-year return period floods, together with the associated 90% uncertainty band, are presented in Figure 14.

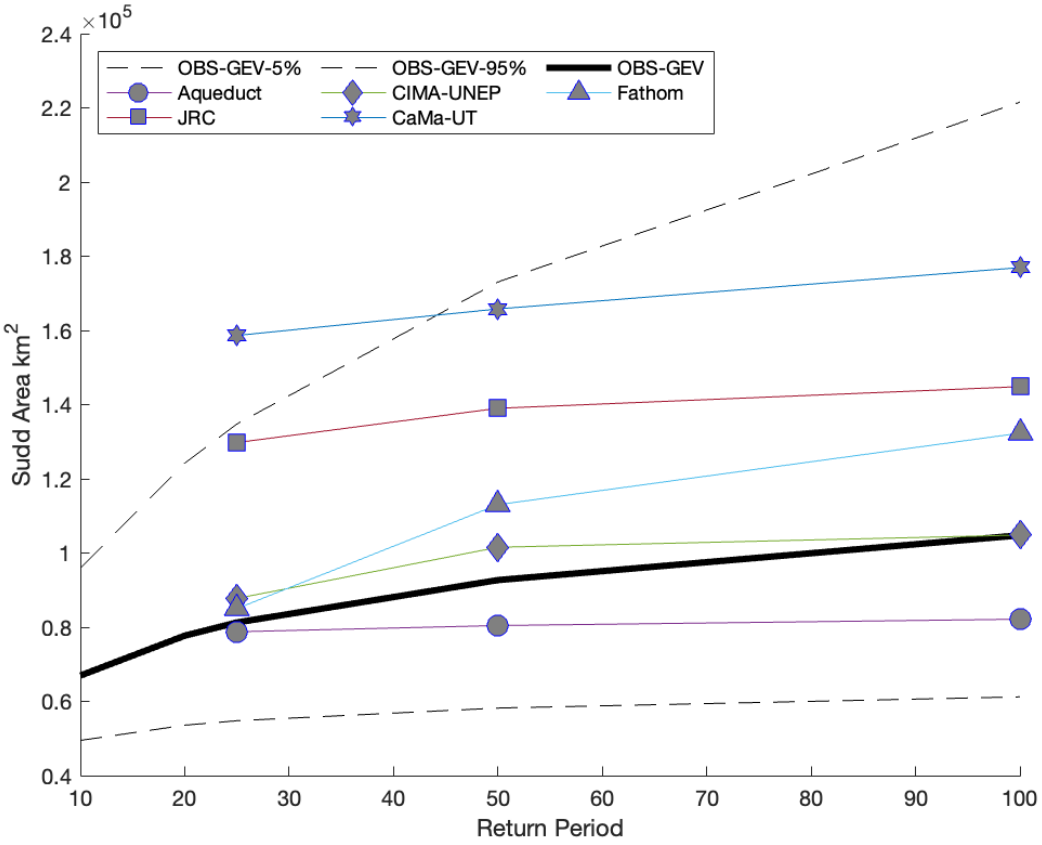


Figure 14: Sudd maximum flooding extent: Satellite-derived estimates and global flood model (GFM) simulated flood extent across different return-period scenarios (10–100-year return periods).

One objective of this analysis was to identify the GFM that most closely reproduced the satellite-observed flood extent. Model skill was assessed by comparing simulated and observed flood extents across equivalent flood-frequency scenarios. In this chapter, flood probabilities refer to annual exceedance probabilities (AEPs) associated with specific return periods. Therefore, the 5%, 4%, 2%, and 1% flood scenarios represent approximately 20-year, 25-year, 50-year, and 100-year return period floods, respectively. These scenarios represent the statistical probability of a flood magnitude being equaled or exceeded in any given year rather than the likelihood of flooding occurring at a specific location in that year.

Figure 14 visually compares the frequency curves from each GFM with the satellite-derived GEV median estimate and the associated 5th and 95th percentile confidence limits. Table 7 presents the root mean square (RMS) error in flooded area between GFM projections and the observed GEV-based estimates for the 20-, 25-, 50-, and 100-year return period flood scenarios (equivalent to 5%, 4%, 2%, and 1% AEP events, respectively). Visually and based on Table 6, the CIMA-UNEP model shows the best agreement with the satellite-observed flood extent.

Table 7: Difference in maximum annual flood extent between global flood model (GFM) projections and GEV-derived satellite estimates for 20-, 25-, 50-, and 100-year return-period flood scenarios (equivalent to 5%, 4%, 2%, and 1% annual exceedance probability events).

	Difference from estimated GEV flooded Area (estimates from 2000 to 2022) (km2)		
GFMs	4%/5% AEP	2% AEP	1% AEP
Aqueduct- 4%	2,501	12,249	22,610
CIMA-UNEP-4%	6,477	8,846	67
Fathom-5%	3,756	20,327	27,540
JRC-5%	48,497	46,312	40,079
CaMa-UT-4%	77,354	73,097	72,167

The differences presented in Table 7, although relatively large, are not unexpected given the challenges of applying global flood models to the Sudd region. The Sudd has unique hydrological and hydraulic characteristics, including extensive seasonal inundation, floodplain storage, vegetation dynamics, and strong interactions between river flow and wetland processes. Global models generally do not incorporate the same level of local calibration or detailed hydrological information available to regional modelling studies. Previous localized modelling efforts (Sutcliffe and Park, 1999; Di Vittorio and Georgakakos, 2021), for example, have incorporated local observations and site-specific parameterization that are not available to global flood models.

4.4.4 Georeferenced population modelling for the Sudd region

Comparing South Sudan and the Sudd region total population estimates (Table 8), including population density among the five population products, the magnitude of the difference in population estimates was observed. To compare population density, the study used South Sudan area, 644,329 km², and the Sudd region estimated area, 326,863 km², as defined for this study.

Table 8: Population estimates for South Sudan and the Sudd region.

Population Products	South Sudan population	SSD Pop density/km²	Sudd region population	Sudd region Pop density/km²
South Sudan population 2008	8,260,490	13.8	4,577,414	14.0
LandScan Pop 2020	10,543,201	16.4	4,333,702	13.3
World Pop 2020 UN adjusted	11,179,641	17.4	4,370,838	13.4
GHSL-Pop 2020	11,203,766	17.4	5,529,445	17.0

S. Sudan pop projected 2020	13,249,925	20.6	7,334,763	22.4
GPW-Pop 2020	14,206,579	22.0	4,733,662	14.5
World Pop 2020 non-UN adjusted	16,826,744	26.1	6,550,256	20.0

The WorldPop- UN adjusted and GHSL-Pop have about the same population estimates for the Sudd region and South Sudan, as both products use the same (UN-adjusted) census data for 2020 as the input data. The GPW estimates to be about 0.4 million population more than does the LandScan for the Sudd region. LandScan predicts the least total population for both South Sudan and the Sudd region. To compare population density for South Sudan and the Sudd region, the study used five georeferenced population products (Figure 15).

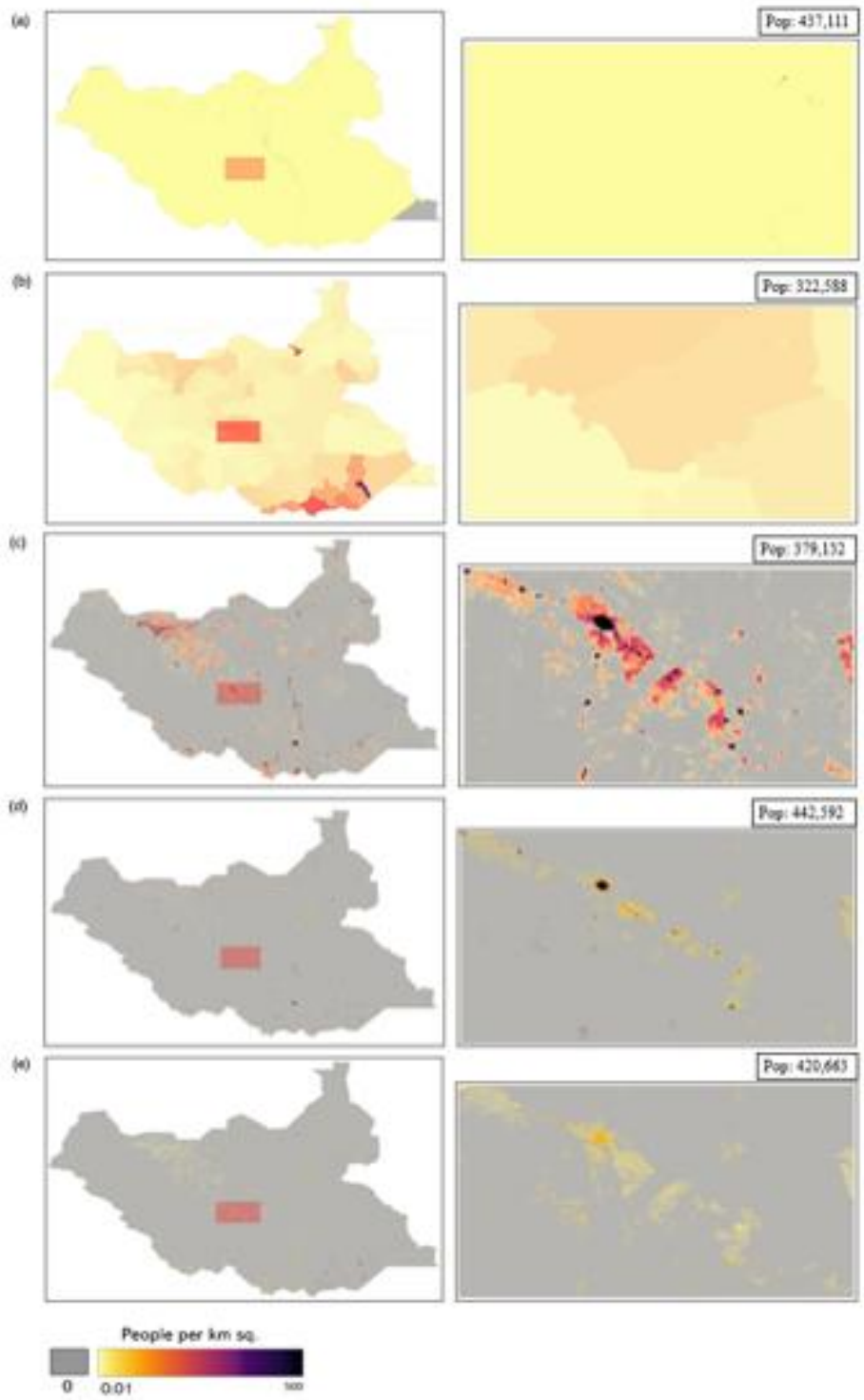


Figure 15: Comparison of population density products: the left column represents population density map of South Sudan - (a) WorldPop – non- UN-adjusted, (b) GPW, (c) LandScan Global, (d) GHSL-Pop, and (e)WorldPop – UN-adjusted- with the inset area; and the right column indicates the population density detailed area - the number of people in the inset area for each product is indicated in the corresponding text boxes.

The LandScan, WorldPop, and GHSL maps show details of the location of settlements in different parts of the country, including clustered population settlement pattern in the Sudd region. There are, however, uncertainties associated with the application of any of these population modelling products. While the gridded population datasets present a static view of population distribution, they fail to account for the dynamics of human migrations that might have occurred between 2008 and 2020. All the products cannot account for migratory populations in the Sudd region as they move seasonally and often residing in less visible shelters that are made of grasses and branches of trees and often located within and under trees. This shortcoming presents challenges in determining dynamic population density and habitations vis-a-vis changing nature of flood risks.

4.4.5 Population exposure calculations

The summary statistics of exposure were calculated first for the Sudd region, then at the South Sudan level. The total exposed and total average population exposed were calculated for each level of analysis at 20, 25, 50, and 100-year return periods using georeferenced population datasets for 2020. Exposure differences calculated for the Sudd region arise when intersecting four different population products with GFMs products across these various simulated food return periods (Figure 16). The comparison framework showing the intersection of multiple Global Flood Models (GFMs) and georeferenced population datasets under different flood return periods is provided in Supplementary Information (Figure 18).

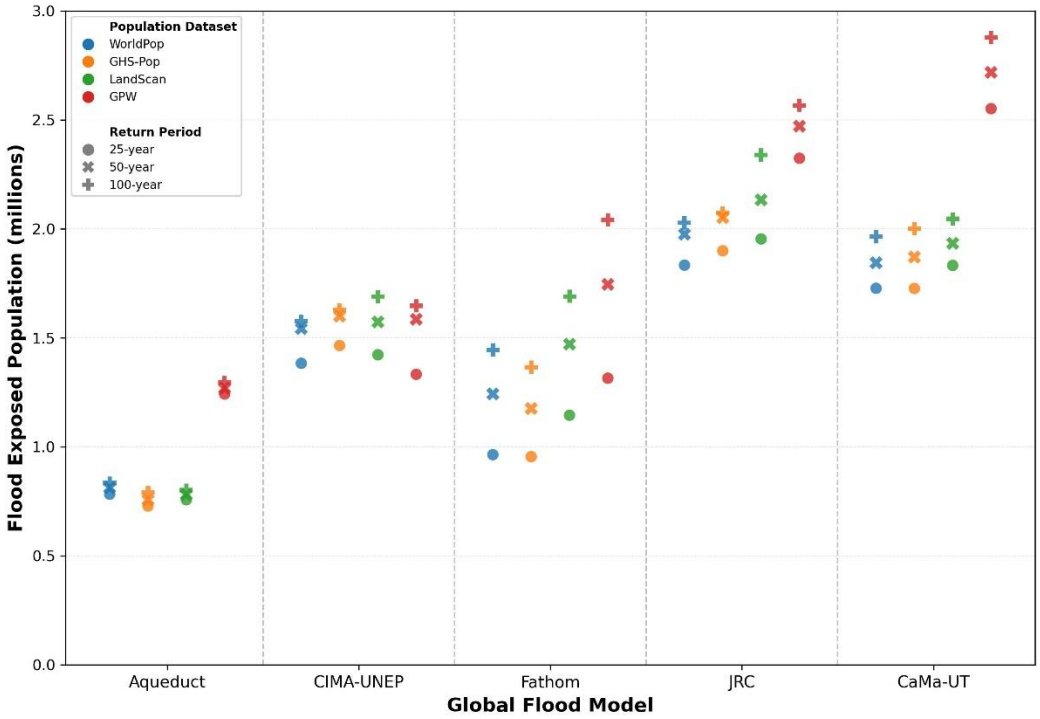


Figure 16: Population exposure for the sudd region: intersecting GFMs and gridded population products.

The estimated population that is modelled for the Sudd region varies between the global population products used in this study. The Sudd population estimates represent the Sudd region that begins at the entrance of the Sudd in Mongalla, Central Equatoria state and includes part of the Bahr el Ghazal and Sobat systems (Figure 5). To compare these populations estimates, the study used the absolute values as modelled by each of the population products, and percentage differences of population exposures, computed by intersecting each population product estimates and simulated flooded area by each of the five GFMs.

The Aqueduct model shows the least exposure for all population data products. The WorldPop product, when intersected with Aqueduct shows almost similar percent exposure across the three return periods, (Figure 16).

GPW estimates the largest population exposures across three return periods, 25-year (2.5 million), 50-year (2.7 million), and 100-year (2.8 million) when intersected with CaMa-UT. In addition to the differences in absolute values of the flooded extent area, the study assessed percentage differences of population exposures. Comparing percentage differences of population exposures between population products captures how each product distributes population density in the Sudd region vis-à-vis GFMs delineation of the wetland extent. All the population products intersected with both JRC and CaMa-UT show high percent exposure to flood risks. The GPW estimate produces the largest population exposure, 54% using the JRC model and 61% using the CaMa-UT model for a 1% probability of flood occurrence. The differences in methods each population product uses to estimate the population and the variations in the estimated flooded area extent attributed to the algorithm configurations of each GFM are reflected in the differences in population exposures for the Sudd.

4.5 Conclusion

This study evaluated and compared multiple global flood models (GFMs) and integrated their outputs with gridded population datasets to quantify population exposure to flood hazards across the Sudd region of South Sudan. Beyond its relevance to South Sudan, the study

demonstrates the broader value of combining multiple flood hazard models and population products rather than relying on a single global dataset for flood risk assessment. The results show that between 0.8 and 2.8 million people are currently exposed to the 100-year return period flood extent, depending on the combination of flood model and population dataset used. This wide range highlights the substantial uncertainty associated with both flood extent estimation and geospatial population mapping, underscoring the importance of explicitly considering these uncertainties when assessing flood exposure.

The intercomparison of the five global flood models reveals strong agreement in identifying the principal flood-prone areas within and surrounding the permanent Sudd wetland, as well as along the confined floodplains, tributaries, and distributary channels of the Sudd Nile. The highest levels of agreement occur around the permanent wetland and seasonally inundated floodplains, reflecting the characteristic hydrological processes through which seasonal floods spill beyond river banks and inundate adjacent landscapes. These areas therefore represent locations where flood hazard estimates are comparatively robust across different modelling approaches.

Comparison of the global flood models with satellite-derived flood observations further highlights both the strengths and limitations of existing datasets. Although discrepancies remain, there is substantial agreement between the modelled flood hazards and MODIS-derived flood extents in areas that experience regular seasonal inundation. Analysis of the MODIS flood record further indicates that the period from 2019 to 2022 represents a distinct flood regime characterized by more extensive, frequent, and persistent flooding than observed previously.

This shift has substantially increased the number of people exposed to flooding, with important implications for livelihoods, human well-being, infrastructure, and long-term economic development across the Sudd region.

The comparison of the four gridded population datasets also demonstrates important differences in the representation of rural populations. WorldPop and GHSL-Pop more accurately reflect the clustered settlement patterns typical of traditional communities located along the tributaries and floodplains of the Sudd Nile. Nevertheless, all currently available georeferenced population products remain essentially static representations of population distribution. Consequently, they do not adequately capture the highly dynamic patterns of seasonal mobility, displacement, and migration that characterize the Sudd region, where populations move frequently in response to flooding, livelihoods, insecurity, and limited census information. This limitation introduces additional uncertainty into flood exposure assessments in data-scarce environments.

While differences remain among the flood models, particularly in remote rural areas of the Sudd floodplains, this intercomparison represents an important step towards improving flood hazard assessment in one of Africa's least mapped flood-prone landscapes. The findings provide the first comprehensive comparison of multiple global flood hazard and population datasets for South Sudan and generate new evidence on the spatial distribution of flood exposure. These results can support flood risk management, humanitarian preparedness, climate adaptation planning, and disaster risk reduction within South Sudan, while also providing a transferable framework for flood exposure assessment in other data-scarce regions across Africa and beyond.

The flood extent estimates presented in this chapter are derived from global flood models that are designed primarily for broad-scale flood hazard assessment and intercomparison. Although these models consistently identify the Sudd as a highly flood-prone landscape, they differ considerably in their representation of wetland-specific hydrological processes, including seasonal water storage, evapotranspiration, vegetation dynamics, floodplain connectivity, and water redistribution. These processes are particularly important in the Sudd, where flood dynamics are governed not only by peak river discharge but also by the accumulation, storage, and gradual movement of water throughout the wetland system. Consequently, differences between the GFM-derived flood estimates presented in this chapter and the Sudd-specific hydrological modelling results presented in Chapter 6 reflect differences in model structure, objectives, and process representation rather than inconsistencies in the findings. The hydrological model developed in Chapter 6 provides a more physically based representation of flood dynamics by explicitly simulating wetland storage and water balance processes and calibrating these against satellite observations.

Overall, this study establishes a robust foundation for understanding flood exposure across the Sudd region while highlighting the uncertainties associated with global flood and population datasets. Building on these findings, future research should integrate improved hydrological modelling with dynamic representations of population movement and adaptive behavior, including seasonal migration, displacement, and livelihood adaptation. Such approaches are essential for developing more realistic assessments of flood risk and for informing sustainable

flood management, climate adaptation, and resilience planning in the Sudd region and other large wetland systems facing increasing hydrological variability under climate change.

Data sharing and data availability

The flood hazards dataset and gridded population dataset are openly available, and their references are included in the last rows in tables 2 and 3 respectively. The MODIS derived Earth observed flood extent data for the Sudd and flood report secondary questionnaire data that support the findings of this study are available from the corresponding author upon reasonable request.

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4.6 Supplementary Information

This supplementary information presents the methodological workflows used to estimate population exposure to flooding in the Sudd region. Figure 17 illustrates the spatial integration of satellite-derived flood datasets and population datasets, showing the analytical steps used to identify populations located within flood-affected areas. Figure 18 provides further detail on the comparative exposure assessment using multiple Global Flood Models (GFMs) and georeferenced population products under different flood return periods. These materials are included to improve transparency regarding the geospatial processing procedures, datasets, and assumptions underlying the population exposure estimates presented in the thesis. They also support interpretation of the results by demonstrating how variations among flood models and population datasets were considered when assessing human exposure to flood risk in the Sudd.

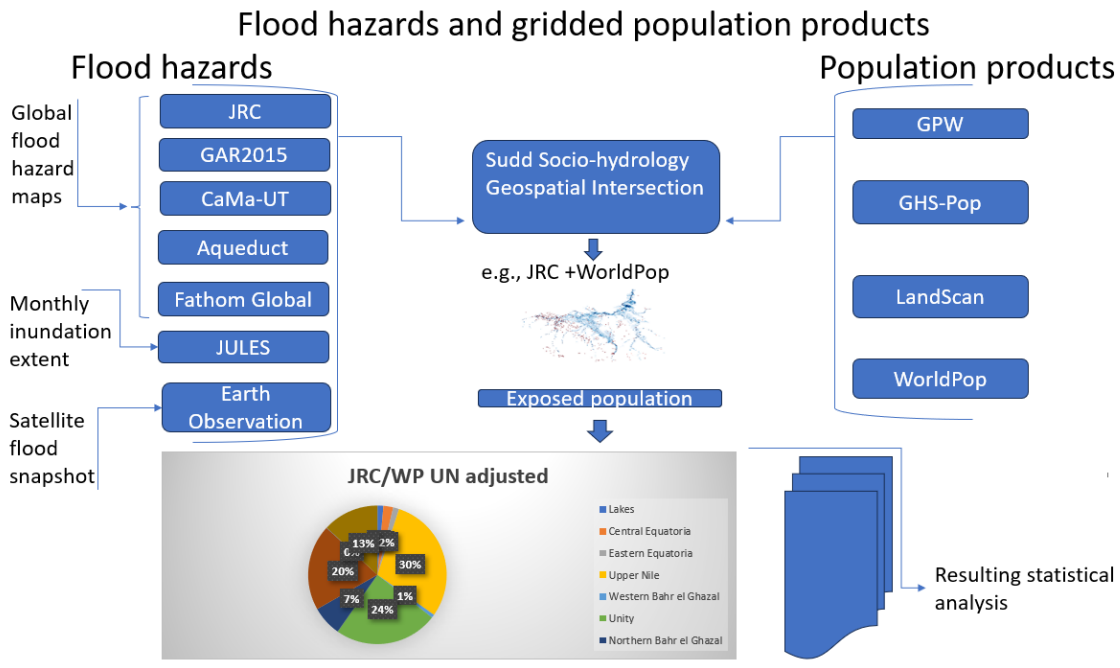


Figure 17: Intersecting flood data and population datasets to derive population exposure in the Sudd region.

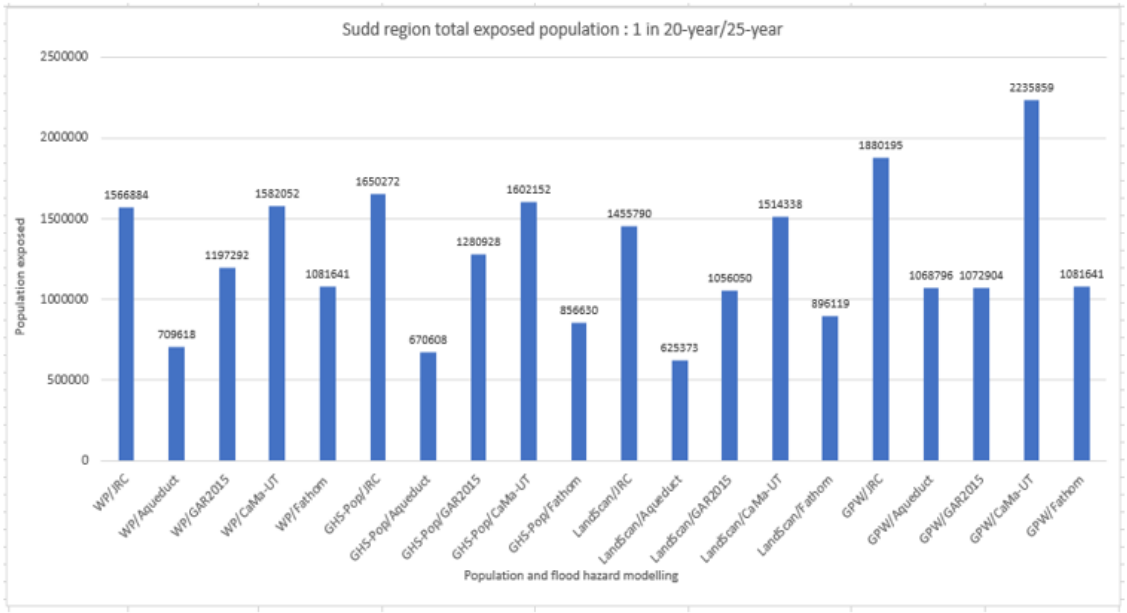


Figure 18: Intersecting five GFMs and four georeferenced population products: 1- in- 20- year return (JRC) and 1- in - 25-year return (CaMa-UT, Fathom, Aqueduct, and GAR 2015).

CHAPTER 5

5 DYNAMICS OF HUMAN ADAPTATION TO FLOOD RISK IN THE SUDD WETLANDS, SOUTH SUDAN

This chapter addresses the second research question that guides the conduct of field study: How does recent extreme flooding (2019-2024) influence migration and perception of changes in the frequency and severity of flooding in the Sudd region? This 5th chapter builds on the previous chapter's known limitation of the application of the global datasets in Sudd region and addresses the second research question by focusing on field study on the changing dynamics of human adaptations the most poverty vulnerable and exposed communities to flood hazards (identified in Chapter 4). The chapter describes the field data acquired through a multi-method approach and evaluates how communities cope with and adapt to riverine hazards, including flood-induced migration responses. The chapter advances a conceptual framework and describes methodological steps for qualitative data analysis of the field data, before presenting key results, discussions, implications, and conclusion. Regional Environmental Change publishes this chapter: Dynamics of human adaptation to flood risk in the Sudd wetlands, South Sudan | Regional Environmental Change | Springer Nature Link. The chapter was co-authored

by Jim W. Hall, Kevin G. Wheeler, Amelie Paszkowski, and Steve Smith-Kroll , who all gave methodological advice, contributed to the conceptualisation, and provided feedback on the text and figures.

Supplementary tables and figures follow the reference list of this chapter.

Abstract

The Sudd is the largest tropical wetland in the world, and its ecosystem services are fundamental to the livelihoods, wellbeing, 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, the study applies a thematic analysis of locally grounded evidence. To address potential limitations associated with qualitative and multilingual research, including dominance, translation, and recall biases, findings were interpreted through diverse community perspectives, cross-checked translations, field observations, and collective intergenerational flood memories rather than individual recall alone. 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 interact to shape adaptation pathways in the Sudd and other climate-sensitive wetland systems. These findings demonstrate that strengthening flood resilience in the Sudd 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.

5.1 Introduction

About 1.81 billion people, 23% of the world population, are directly exposed to flood depths greater than 0.15 meters 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 population movements, as displacement is most likely to occur where climate hazards interact with high vulnerability and low adaptive capacity (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) (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 savannah and extensive floodplains around the Sudd's permanent wetlands and seasonal swamps (Figure 1). The Sudd 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 welfare 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 rain-fed 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 1960s, 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 historic flooding have 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 l., 2019; Thiede et al., 2016; Chung et al., 2022a; Agnew et al., n.d.; Kroll-Smith and Leon-Corwin, 2023), this chapter 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; Mao, 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. 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 interact to 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 and variability of the Sudd within the Nile River system have been studied by numerous investigators (such as Petersen, 2008; Sutcliffe and Brown 2018; Persico et al., 2024; 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 region, which is hindering informed decision-making in the face of investment planning for flood risk management in the country. 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 these dynamic interactions and has the potential to inform communities' resilience plans and flood risk management planning at the community, state, national, and the Sudd regional levels.

5.2 Study area

5.2.1 Geography, climate, and environment

At the sub-national 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 (Figure 19), 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 field work 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 (Powell et al., 1992) 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 1,300 mm. The heaviest rainfall occurs in the southern upland areas and decreases towards the north. Western Equatoria and highland parts of Eastern Equatoria receive between 1,200 and 2,200 mm of rainfall annually (Lukwasa, 2022; Climate Change Knowledge Portal, World Bank, 2025).

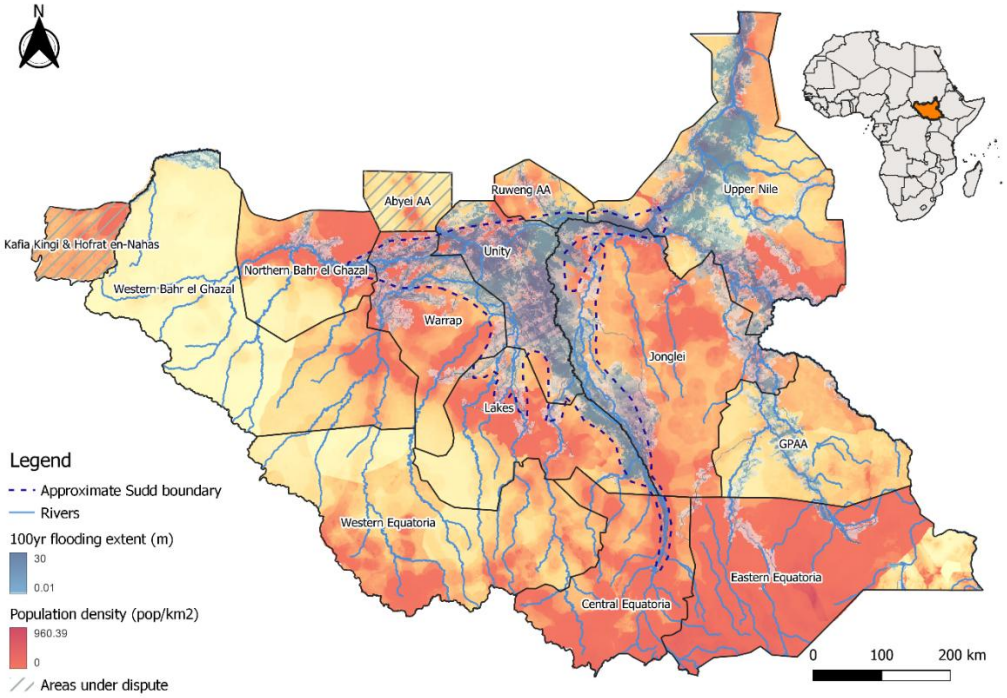


Figure 19: Map of the approximate Sudd boundary in the context of population density and the 100yr flood depth of South Sudan. Note, there is no official definition of the boundary of the Sudd; it has been delineated based on flood extents and a compilation of existing (differing) delineations in literature. The map was created by overlaying population density for the year 2020 from WorldPop (Tatem, 2017), with the 100yr flood extent from the global GLOFRIS flood model (Ward et al., 2013). Note, the flood data is for visualization only; flood information for this study is compiled from community-level information.

5.2.2 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 (Figure 20), 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 m3/s of water downstream into South Sudan (Watchers News, 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.

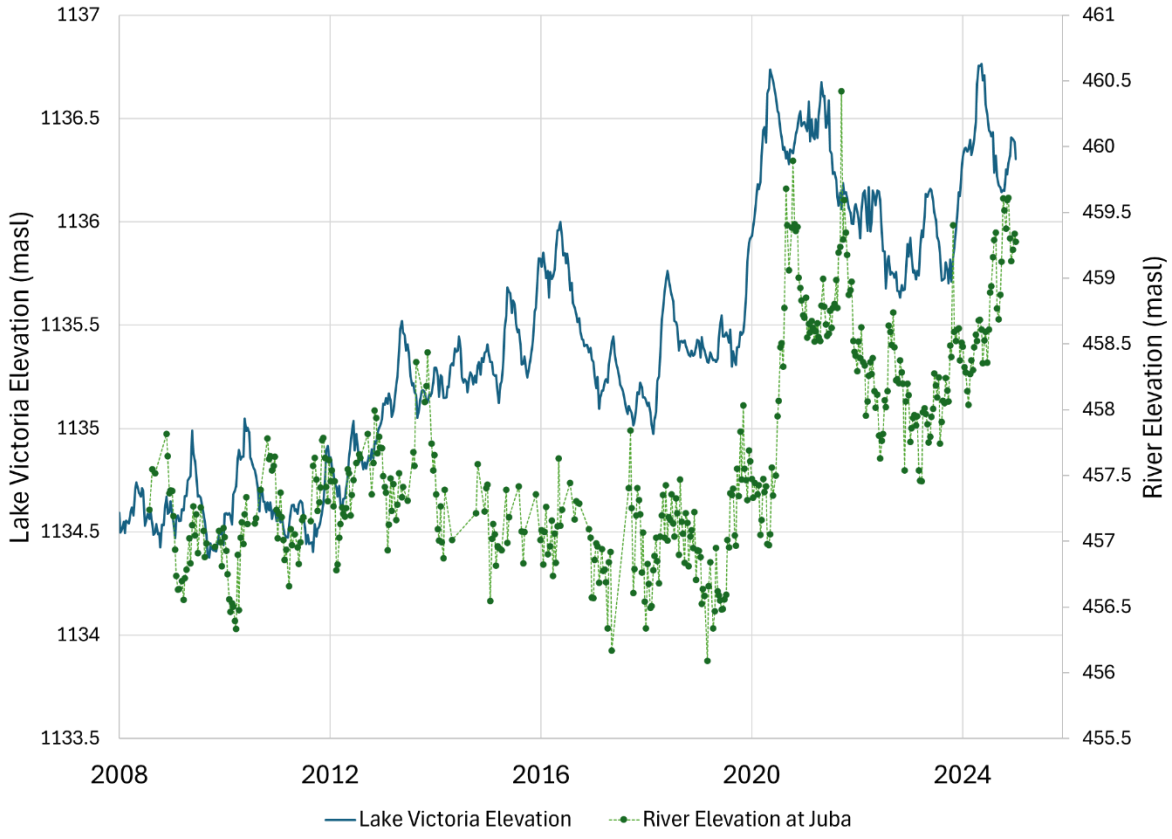


Figure 20: Comparing Lake Victoria elevation and river Nile elevation at Juba(data source: Dahiti-Schwatke et al, 2015) Juba.

5.2.3 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; Gillin, 2015; Tekola, 2024; 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, 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 (Figure 21).

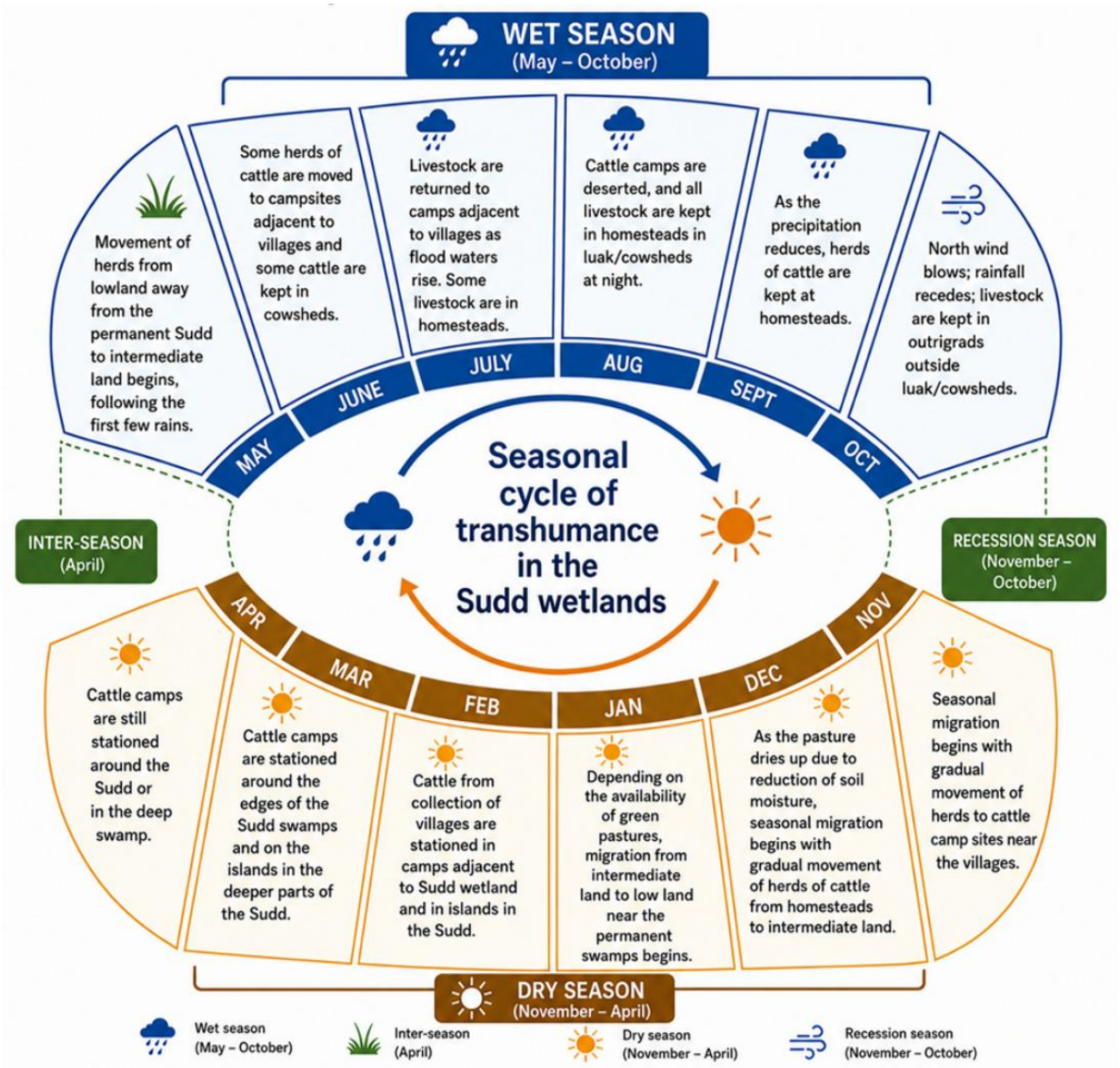


Figure 21: Seasonal cycle of annual transhumance in pastoral livelihoods of the Sudd region (Adapted from de Mabior, 1981).

Figure 21 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.

5.3 Data and methods

The field research 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 methodological approach was adopted because conventional quantitative modelling 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 approach 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.

5.3.1 Fieldwork design

The field research 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. While the preceding modelling analysis quantified spatial patterns of population exposure to flood hazards, this field component 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. The field research was planned prior to data collection and undertaken between February and June 2024 across selected locations within the Sudd region of South Sudan. The study covered the major floodplain states of Jonglei, Unity, Lakes, and Upper Nile, as well as Warrap in the adjacent Bahr el Ghazal floodplain, with Juba included as a strategic location for engagement with diverse stakeholders and participants from across the region. These locations were selected because of their historical and contemporary exposure to flooding, their representation of different livelihood systems, and their relevance for understanding changing patterns of adaptation and mobility.

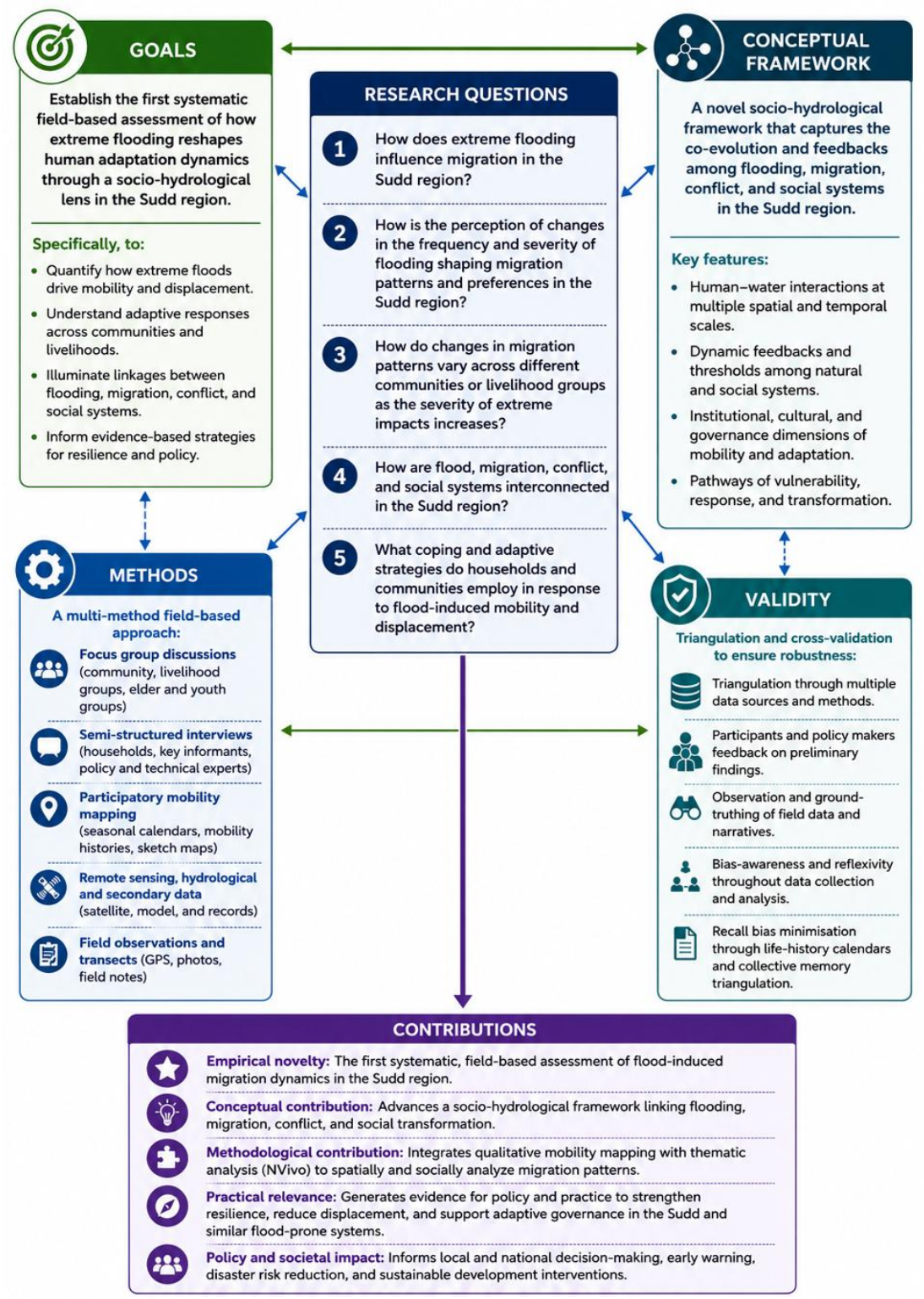


Figure 22: Conceptual overview of the research design, showing the relationships between the study goals, research questions, socio-hydrological conceptual framework, methodological approach, validation strategy, and research contributions for investigating flood-induced migration in the Sudd region of South Sudan (Adapted from Maxwell, 2013).

The fieldwork design (Figure 22) 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. In the Sudd context, communities have historically adapted to seasonal flooding through livelihood mobility, transhumance, fishing strategies, flood-recession agriculture, and temporary relocation. However, increasing frequency and duration of extreme floods may alter these established relationships between people and water. The field study was therefore designed to examine whether existing adaptation pathways remain effective under intensifying flood conditions, and whether extreme flooding is producing new patterns of displacement, migration, and settlement change.

Conceptual overview of the research design, showing the relationships between the study goals, research questions, socio-hydrological conceptual framework, methodological approach, validation strategy, and research contributions for investigating flood-induced migration in the Sudd region of South Sudan. (adapted from Maxwell, 2013).

5.3.2 Field sites in the Sudd region

This section of the thesis is based on field study conducted in 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 multi-source evidence approach. The study 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 field research covered all these areas. 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 (Figure 23) are representative of the Sudd region geography and the populations. The detailed administrative structure of each of the counties visited is included in the supplementary information.

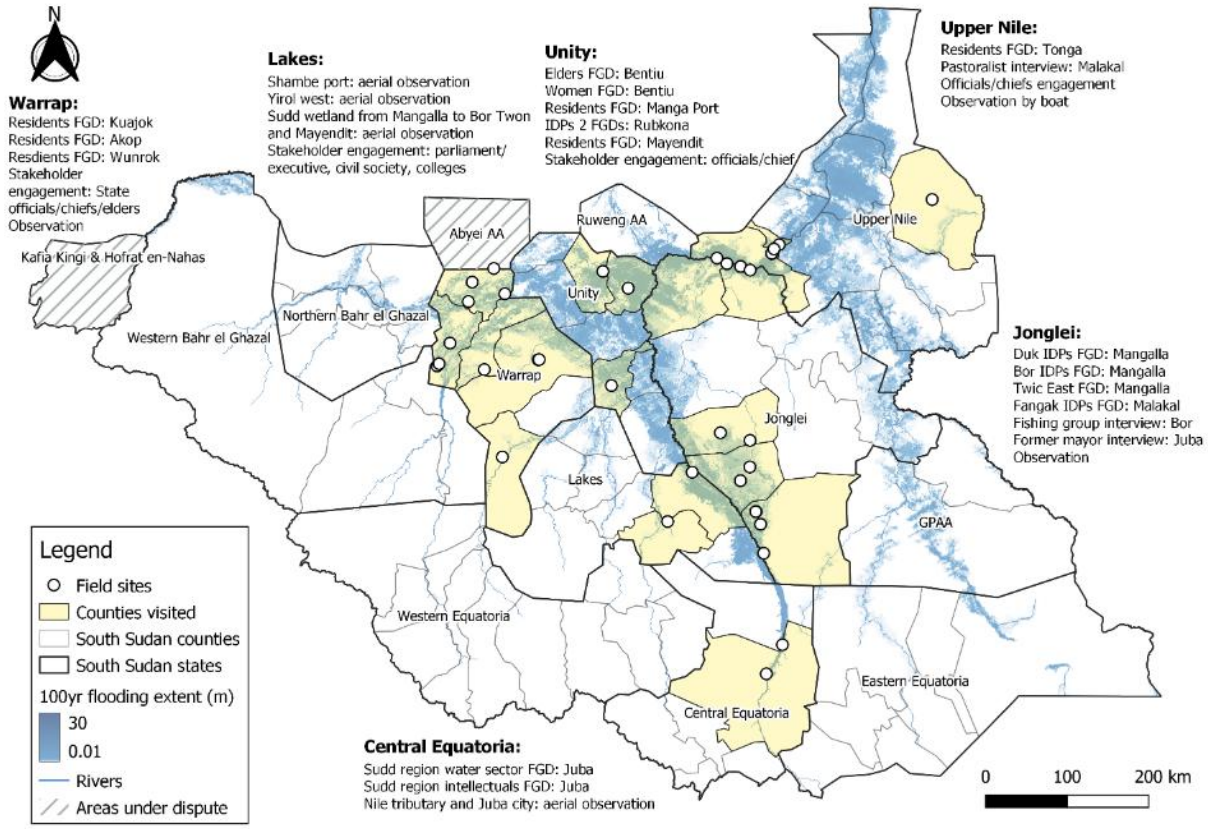


Figure 23: Fieldwork locations visited in the Sudd region for this study, including sites where focus group discussions, interviews, and direct field observations were conducted (based on GPS coordinates collected during field research). The 100-year flood extent from the global GLOFRIS flood model (Ward et al., 2013) is included for visualization of flood hazard context only and does not represent the specific locations of qualitative data collection.

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.

In Unity State, qualitative data collection was conducted in Bentiu, Rubkona, Mayendit County, and Manga Port in Guit County. A total of five focus group discussions were undertaken in the state, including three in Bentiu and Rubkona, one in Mayendit County, and one in Manga Port. These discussions explored community experiences of flooding, livelihood impacts, displacement patterns, and local adaptation strategies.

In Warrap State, three focus group discussions were conducted across different locations. One discussion was held in Kuajok with policymakers and water-sector experts to capture institutional perspectives on flood risk management. Another was conducted in Akop Payam, Tonj North, involving community elders, youth, and women to examine local knowledge, vulnerability, and adaptation practices. A third focus group discussion was undertaken with community members in Wunrok to document community experiences of changing flood conditions and associated livelihood impacts.

Fieldwork in Upper Nile State combined direct observation and qualitative engagement. A speedboat observation survey was conducted along the water corridor from Malakal to Tonga in Panyikang County to document flood conditions, hydrological features, settlement patterns, and accessibility challenges. Additional observations were conducted in Malakal, including flood and landscape assessments and walking interviews in cattle camps to understand pastoral mobility and adaptation practices. A focus group discussion was also conducted with local community members in Panyikang County.

In Jonglei State, fieldwork involved both observational and participatory approaches. Walking interviews were conducted in Aduar, north of Bor County, while observations of flood protection infrastructure, including dikes, were undertaken in Bor town. Focus group discussions were conducted in Bor County, Duk County, Twic East County, and Fangak County to examine community perceptions of flood risk, livelihood transformation, displacement, and local adaptation strategies. The administrative structures of the study counties and their constituent payams are provided in Supplementary Information 5.8 (Figures 28-42) to contextualize the governance and territorial arrangements within which flood exposure, resource access, and human mobility responses occur.

In Central Equatoria State, Juba was selected as an adjacent research location to facilitate engagement with national-level stakeholders and respondents connected to flood-affected areas of the Sudd. Focus group discussions were conducted with internally displaced persons (IDPs) in Mongalla Payam, while semi-structured interviews and FGDs were undertaken with water-sector experts, policymakers, and other key informants in Juba. These engagements provided broader perspectives on flood governance, institutional responses, and regional flood management challenges. The administrative structures of the study counties and their constituent payams are provided in Supplementary Information (section 5.8) to contextualize the governance and territorial arrangements within which flood exposure, resource access, and human mobility responses occur.

In addition to site-based qualitative research, an aerial survey was conducted along a transect extending from Mongalla (Mangalla) Payam in Central Equatoria, across Bor town in Jonglei State, over Shambe in Lakes State, and to Mayendit in Unity State. These aerial observations were used to document broader flood extent, landscape characteristics, settlement distribution, and patterns of human exposure to flooding. Together, these field activities provided a multi-scalar understanding of flood risk and human adaptation across the Sudd region.

5.3.3 Data and field research methods

The field data were collected from 18 February to 4 June 2024 using various methods (Table 9). interviews, qualitative mobility mapping, and observation. The study was conducted with participants selected from different communities and livelihood groups, including pastoralists, subsistence farmers, fishers, and internally displaced persons (IDPs) who depend on humanitarian food assistance.

The selection of internally displaced persons (IDPs) for this study required careful consideration given the complex displacement context of South Sudan. Displacement in South Sudan is rarely attributable to a single cause; rather, conflict, insecurity, livelihood disruption, and environmental hazards frequently interact to shape patterns of human mobility. Decades of armed conflict, political instability, and recurrent humanitarian crises have resulted in populations experiencing multiple episodes of displacement. Consequently, many displacement sites across the country contain populations displaced at different times and for different reasons, including conflict-related displacement and more recent climate- and flood-related displacement.

Against this background, this study did not treat IDPs as a homogeneous population. Instead, participants were selected based on their experiences of flood-induced displacement associated with the major flooding events that affected the Sudd region between 2019 and 2024. The purpose of this approach was to capture the experiences, vulnerabilities, coping mechanisms, and adaptation strategies of populations whose displacement was directly associated with extreme flooding. The identification of flood-induced IDPs was based on respondents' accounts of their displacement history, including place of origin, timing of movement, immediate cause of displacement, and the circumstances surrounding relocation.

The flood-induced IDPs encountered during the fieldwork represented different scales of displacement. The first category consisted of populations displaced within their own counties, payams, or neighboring villages. These households were forced to leave their homes due to rising floodwaters but remained within their broader social and administrative territories. For example, in Mayendit County, Unity State, focus group discussions included both resident communities and households displaced from nearby payams and villages because of flooding. These respondents provided insights into local flood impacts, livelihood disruption, changing settlement patterns, and community-based adaptation practices.

The second category consisted of populations displaced within their respective states but outside their original counties. In Unity State, for example, households from Mayom, Guit, and Rubkona counties relocated to Bentiu following severe flooding. Bentiu represented a particularly complex displacement environment because the town had already hosted large numbers of populations displaced by armed conflict, including those displaced during the 2013 civil war and residing in POC sites prior to the extreme floods of 2019–2024. However, the

flood-induced IDPs interviewed for this study were clearly distinguished from earlier conflict-displaced populations. Many flood-displaced households were located in other areas of Bentiu town, including areas protected by the major dike system constructed by the government and humanitarian agencies. Focus group discussions in Bentiu were therefore conducted only with participants who reported that flooding during the 2019–2024 period was the primary cause of their displacement.

The third category involved inter-state displacement, where flood-affected populations crossed administrative boundaries into neighboring states. For example, households from Duk County, Bor County, and Twic East County in Jonglei State relocated to Mangalla in Central Equatoria and to parts of Lakes State following severe flooding. Mangalla also hosted populations displaced by the 2013 conflict; however, flood-induced arrivals occurred later and were settled in different parts of the town. Community leaders assisted in identifying individuals whose displacement was specifically associated with flooding rather than conflict. The interviews and group discussions conducted in Mangalla therefore focused exclusively on flood-displaced populations. A similar situation occurred in Malakal, Upper Nile State, where populations displaced from Fangak County in Jonglei State sought refuge following extensive flooding. While Malakal has historically hosted conflict-displaced populations, including those residing in POC sites, flood-induced IDPs arriving during the 2019–2024 flood period were located separately within the town. The focus group discussions undertaken in Malakal were conducted with flood-displaced respondents whose movements were associated with recent flooding rather than earlier conflict-related displacement.

Overall, although some displacement locations included populations affected by both conflict and flooding, the study did not treat all IDPs within these sites as equivalent. The sampling

strategy deliberately focused on individuals and households who identified flooding as the immediate trigger of their displacement during the 2019–2024 flood period. This distinction is particularly important in the Sudd region, where environmental hazards occur within a broader context of political fragility, insecurity, limited infrastructure, and humanitarian vulnerability. The findings therefore represent the experiences of flood-induced displacement while recognizing that flood risk and displacement in South Sudan are embedded within wider processes of social, political, and environmental change.

While the study differentiates between community groups for analytical purposes, in many instances populations encountered in the field were either displaced, residing in their home locations, or located in transitional settings such as cattle camps. For analytical clarity, community groups were classified according to their “administrative units”, understood as the locations respondents identified as their primary place of origin or home. In addition, some FGDs and semi-structured interviews were conducted with water-sector practitioners from relevant states and administrative areas, as well as with key informants and local experts from across the Sudd region.

While the study differentiates 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. The study 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.

Table 9: 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.

This recruitment was based on clear instructions provided by the research team to include a diversity of participants in terms of age, gender, and coming from a representative sample of geographic areas. 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 several 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.

Given the linguistic diversity of the study area, some interviews and focus group discussions were conducted with the support of local research assistants who also served as interpreters when translation was required. These individuals played an important role beyond literal translation by facilitating communication between the researcher and participants and ensuring that local expressions, cultural meanings, and context-specific concepts were accurately conveyed. Their familiarity with the communities, livelihood systems, flood experiences, and

social dynamics of the study sites helped maintain the contextual integrity of participants' responses. The involvement of interpreters was particularly valuable during discussions of sensitive topics, including displacement, conflict-related experiences, livelihood disruptions, and mobility decisions, where direct word-for-word translation could risk losing important meanings. Interpreters were briefed on the objectives of the research, ethical considerations, confidentiality requirements, and the importance of preserving participants' intended meanings rather than summarizing or altering responses. Where translation was used, the researcher cross-checked interpretations through follow-up questions and clarification with participants to ensure accuracy and consistency. The translated transcripts and field notes were subsequently analyzed thematically, with attention to both the content of responses and the socio-cultural context in which they were expressed.

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 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.

Finally, 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 thirteen community

key informants was based on the snowballing sampling method, a technique in which participants were 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.

The FGDs and interviews also generated spatial-temporal data through the reconstruction of collective flood memories among the communities in the Sudd region from 1943-2023. This period is chosen because it covers the memories of three to four generations aged 18 to 80 years old. This period covers both historical and contemporary human-flood interactions across the Sudd region. 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 (Figure 24).



Figure 24: Focus group discussions in 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 taken by Dak Meat Kueiguong, Bentiu Town, Unity State).

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 21st 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. As part of the FGDs and semi-structured interviews, the study uses qualitative mobility mapping while interviewing participants, to understand pastoralists' movements, journeys, and experiences related to accessing resources or services. Group discussions and collaborative mapping sessions were held, where participants across different social groups drew, sketched, and 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 enabled the study 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 qualitative mobility mapping exercise generated participant-produced sketches on paper during focus group discussions. These sketches were used as participatory tools to elicit information on seasonal movements, changing migration routes, and flood-related mobility adaptations. However, the original drawings were informal working maps with poor reproduction quality and lacked sufficient spatial accuracy for inclusion as thesis figures. The analytical value of the exercise was therefore captured through field documentation, coding, and thematic interpretation rather than through the presentation of the sketches themselves.

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. All the field activities were conducted in accordance with the approved ethical protocol and University guidance for research involving human participants. The following section outlines the ethical principles and practical procedures that guided participant engagement, informed consent, data protection, researcher reflexivity, and risk management throughout the fieldwork process.

Ethical design and community-based research approach

The ethical considerations were embedded within the design of the study from the outset. The research aimed to understand how flood-affected populations experience and adapt to changing flood risks in the Sudd region, with particular attention to migration, livelihood transformation, and community responses. The fieldwork was designed as a participatory qualitative study using focus group discussions (FGDs) and semi-structured interviews with community members and key informants. These included farmers, pastoralists, fishing communities, internally displaced persons (IDPs), chiefs, elders, and oral historians.

The decision to conduct interviews and discussions within participants' own social and environmental settings—such as villages, settlements, cattle camps, and other livelihood spaces—was both methodological and ethical. It reduced barriers between researcher and participants, enabled participants to communicate through their own experiences, and recognized communities as holders of knowledge about the Sudd socio-hydrological system.

Given the sensitivity of research conducted in a fragile and politically complex environment, the study was framed explicitly as an academic and scientific investigation of flooding, livelihoods, and adaptation rather than a political inquiry. Participants were informed that the research focused on their experiences of environmental change and adaptation rather than political opinions or advocacy. Political actors and individuals whose participation could introduce additional risks were excluded from the study.

Informed consent and voluntary participation

A central ethical principle of the fieldwork was ensuring that participation was voluntary and based on informed consent. Before participation, individuals were provided with information explaining the purpose of the study, the nature of their involvement, potential risks and benefits, confidentiality arrangements, and their right to decline participation or withdraw. Consent was obtained through written or verbal procedures depending on participant circumstances and literacy considerations. For focus group discussions, verbal consent was obtained before discussions commenced, while interviews with chiefs, elders, and oral historians involved either written or oral consent supported by information sheets and researcher explanations.

Participants were informed that withdrawal was possible at any stage during fieldwork, subject to the practical limits of withdrawal after anonymization, transcription, and analysis.

Protection of vulnerable participants and minimization of harm

Although the study did not specifically target legally defined vulnerable groups, many participants were living with heightened vulnerability due to repeated flooding, displacement, livelihood losses, and environmental uncertainty. The research therefore adopted a precautionary approach to avoid causing additional harm. Questions were carefully designed to focus on participants' experiences of flooding, mobility, and adaptation rather than traumatic personal histories unless participants chose to discuss them. The researcher recognized that discussions about displacement, loss of property, and deaths associated with flooding could generate emotional distress. To address this, interviews and FGDs were followed by debriefing, and the researcher and local partners monitored participant wellbeing after discussions. Where signs of distress occurred, participants were given additional support through discussion and, where necessary, referral to trusted community structures including traditional leaders, church leaders, or nearby health services.

The researcher also reflected on his own positionality as a person with lived experience of the Sudd region and displacement. This awareness informed a reflexive approach throughout the research process, recognizing both the value and potential influence of personal experience in interpreting community narratives. The ethics process encouraged the researcher to critically examine power relationships and ensure that communities were treated as partners in knowledge production rather than merely sources of data.

Confidentiality, anonymity, and research data management

Because the research collected personal experiences, photographs, recordings, and demographic information, protecting confidentiality was a major ethical consideration. The study followed the principles of responsible data management under the UK General Data Protection Regulation (UK GDPR) and University of Oxford research data requirements. Data collected included consent records, field notes, photographs, audio recordings, and interview transcripts. These materials were securely stored in the University of Oxford's approved Nexus365 OneDrive system. Access to raw research data was restricted to the researcher and supervisory team, with external collaborators not granted access to original identifiable data. Participant confidentiality was maintained through careful handling of names and personal details. Where appropriate, data were pseudonymized during transcription and analysis. Participants were also given choices regarding whether their names, photographs, occupations, or locations could appear in research outputs.

Ethical management of interpreters, research assistants, and local collaborators

Because fieldwork was conducted across diverse linguistic communities, local interpreters, translators, and research assistants were required to support communication and data collection. Their involvement was managed through explicit ethical procedures. Before fieldwork, local assistants were briefed on research ethics, confidentiality requirements, and responsible handling of participant information. They were also required to sign confidentiality agreements confirming that participant information, recordings, notes, and research materials would remain

confidential and only be used for the approved research purposes. To reduce the possibility of accidental data loss or disclosure, research materials and recording devices were controlled by the researcher and transferred to assistants only during data collection activities before being returned immediately afterwards.

Researcher safety and fieldwork risk management

Ethical responsibility extended beyond participant protection to include the safety of the researcher and field team. Due to the remote nature of the Sudd wetland, fieldwork involved potential risks including difficult terrain, malaria exposure, insecurity, and travel constraints. A separate departmental travel risk assessment was completed and approved before fieldwork commenced.

Risk mitigation included careful travel planning, local support arrangements, communication procedures, appropriate health precautions, avoidance of unnecessary exposure after dark, and coordination with relevant local networks. The research team maintained awareness of the broader political context while ensuring that field activities remained focused on the scientific objectives of understanding flood risk and adaptation.

Equity, representation, and ethical reciprocity

The research sought to promote equitable participation across different social groups affected by flooding. Attention was given to diverse livelihood groups, including farmers, pastoralists, fisher communities, and displaced populations. The study also considered gender and

generational dimensions by creating opportunities for participation among women, younger community members, and elders.

While participants did not receive payment for participation, the study aimed to provide broader benefits through generating evidence that could support improved flood risk management and sustainable development in the Sudd region. Overall, the ethical approach adopted in this research ensured that the study was conducted with respect for participants, communities, and local knowledge systems. Ethical approval was therefore not treated as a procedural requirement alone but as an integral component shaping the research questions, field methods, data collection practices, and interpretation of findings.

5.3.4 Data transcription and 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, the study uses NVivo, a qualitative data analysis (QDA) software program developed by Lumivero and used to organize, analyze, and visualize unstructured data like interviews, surveys, social media, and audio/video. The study uses NVivo to identify themes, conduct mixed-methods research, and manage and aid analysis of the field data. After the translation of all the transcripts from different South Sudanese ethnic languages to English, 18 documents were created (i.e., one document per FGD/interview) of all field data and imported them into NVivo.

After transcribing the field data, the study used thematic analysis within NVivo to understand participants lived experiences, as well as their views or stories about flooding and its impacts. The study uses 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, the initial codes were created (i.e., predetermined themes from the transcripts) and iteratively categorized the qualitative data into themes (Figure 25).

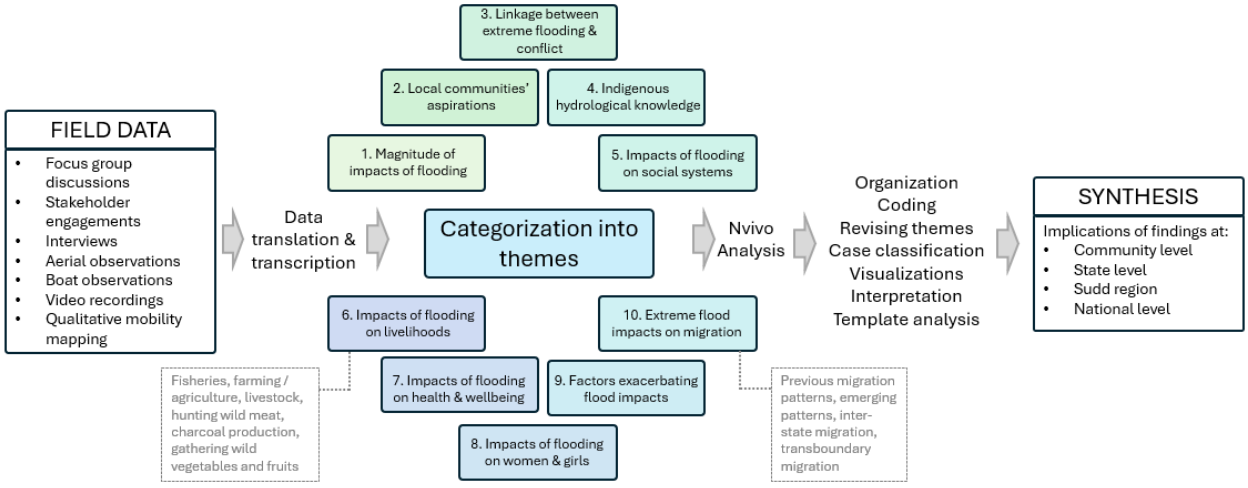


Figure 25: Methodological steps for qualitative data analysis using NVivo. The analysis for this study are based principally on seven migration related themes: 1, 3, 4, 5, 6, 9, and 10.

The coding of themes was an iterative process, with themes added and revised as they emerged in the captured data. To ensure the analysis is not sensitive to the first 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. The code structure developed for the thematic analysis of the field data, including the organization of codes under the ten major themes, is provided in the Supplementary Information (Table 10) to demonstrate the analytical framework used to systematically interpret participants' experiences, perceptions, and adaptation responses. By assessing the number of occurrences of themes, the study can quantify their relative importance (e.g., under Theme 10, the study 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. Overall, this fieldwork design provided a systematic framework for investigating the Sudd as a coupled human–water system. By combining hydrological understanding with community-based evidence, the research was able to examine not only where flood risks occur, but how those risks are experienced, interpreted, and transformed into adaptive decisions by affected populations.

5.3.5 Uncertainties and assumptions in the methodology

While the study 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. These power dynamics among the participants may have influenced the discussions by focusing more on certain themes and experiences. 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 field notes and researcher observations.

Moreover, 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, 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.

5.4 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. Section 4.1 addresses flood impacts; Section 4.2 examines how perceived changes in flood regimes influence migration; Section 4.3 explores differences among communities and livelihood groups; and Section 4.4 examines interactions between flooding, migration, conflict, and social systems.

5.4.1 Impacts of extreme flooding in the Sudd region

The results reveal that recent flooding in the Sudd region 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 (Figure 7) have far exceeded previous levels and have not receded in five years in most of the field 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.



Figure 26: (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). Additional field photographs documenting flood conditions, affected landscapes, and community responses are provided in the Supplementary Information (Figure 44) to illustrate the environmental context and lived experiences associated with flood exposure and adaptation in the study areas.

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

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 floodwater that undermine land-based livelihoods create productive aquatic environments, increasing access to resources such as fish and water lilies.

5.4.2 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 1960s 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 flood waters 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 hydrologic 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.

5.4.3 Migration patterns and preferences across different communities

The higher shift in the flood regime, coupled with the resulting environmental risks, have limited the availability of habitable space, resulting in migration. While the majority of populations across the Sudd region experienced flood-induced migration between 2019-2022, 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 (Figure 27). 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 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 are 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 available or desirable for all households. This also aligns with this finding showing limited long-distance migration among elderly populations in Unity State.

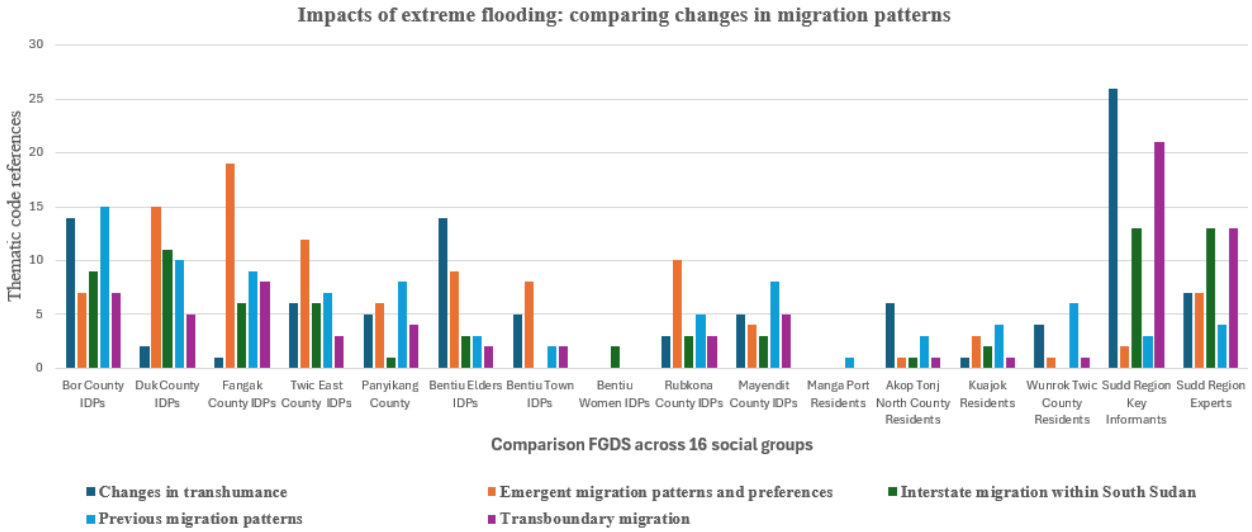


Figure 27: Comparing migration patterns across 16 different social groups. These response categories are related to five sub themes (graph legend) of migration. "Previous migration patterns" refers to similar routes and patterns taken now as during past flood events; "emergent migration patterns and 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 the other.

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.

5.4.4 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 the 16 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 spatial-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 1980s, 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 transformed 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.

5.5 Discussion

This study investigates the changing dynamics of human responses to flooding and how these changes influence human well-being 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.

5.5.1 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 region. 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 of 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 floodwater 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 water 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 history, 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 cross-border 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 appropriate local 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.

5.5.2 State and Sudd region 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-communal tensions. As floodwater reduces 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 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 cross-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 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.

5.5.3 Long-term social transformation and adaptation pathways

The preceding discussion demonstrates that responses to flooding in the Sudd unfold across multiple spatial and temporal scales rather than through a simple sequence of cause-and-effect relationships. Figure 28 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

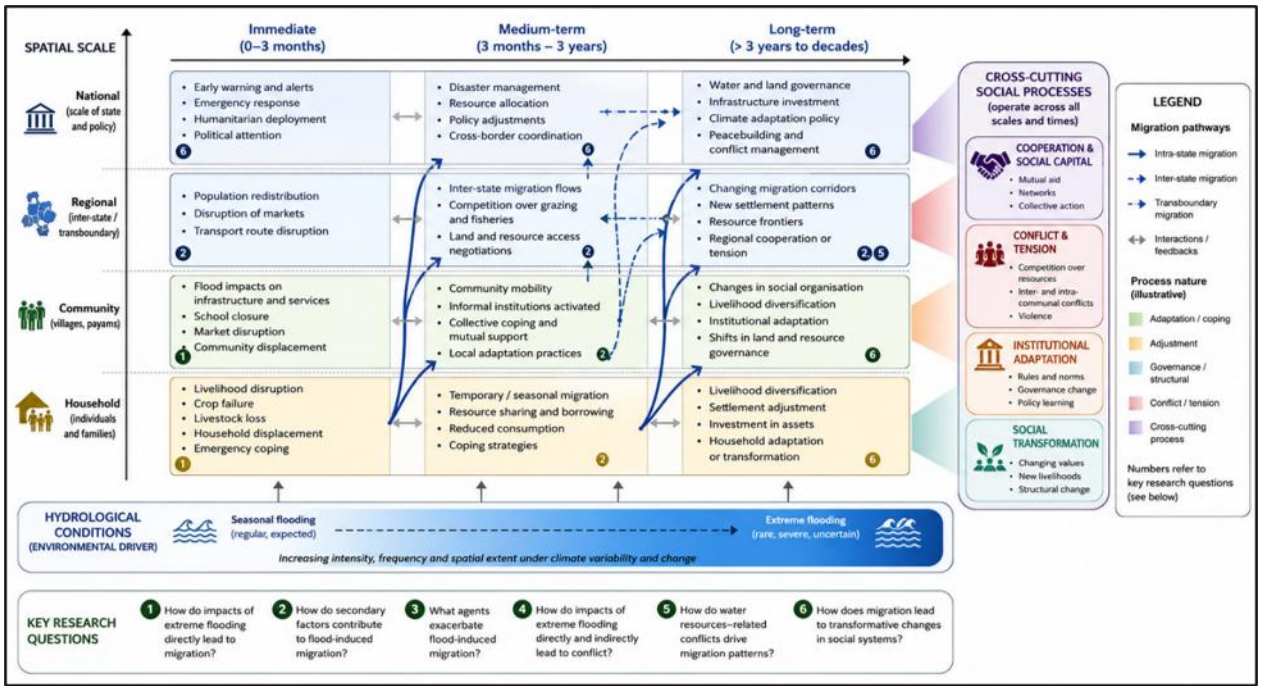


Figure 28: Spatial and temporal dynamics of flood-induced adaptation, migration, and social change in the Sudd.

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 field research 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 centres, 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.

5.5.4 Research limitations

This study addresses an important but underexplored dimension of climate adaptation in a region where primary data collection remains extremely challenging. Conducting field-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.

5.6 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).

5.6.1 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; Frazier 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.

5.6.2 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.

5.6.3 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 wellbeing 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).

5.7 Conclusion

This chapter of the thesis is based on field study that was conducted 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 cross-border migration, which are dependent on the differing experiences of past flood impacts.

The 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.

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 region. 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 socio-economic 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 socio-economic 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 region.

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 socio-economic change.

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5.8 Supplementary Information

Purpose and relevance of administrative structure diagrams

The supplementary materials presented in this section provide an overview of the administrative structures (Figures 29-43) of the counties, payams, and other local administrative units where the field research was conducted. These diagrams are included to contextualize the socio-political and institutional settings within which flood exposure, livelihood practices, and human mobility decisions occur. In South Sudan, administrative boundaries are not merely geographical divisions; they influence governance arrangements, access to public services, allocation of humanitarian assistance, resource management, and relationships between communities. Therefore, understanding the administrative organization of the study areas is important for interpreting the findings on adaptation, displacement, and mobility responses to flooding.

The administrative structures also provide important context for understanding the role of boundaries in shaping human mobility within the Sudd region. Flood-related movements frequently occur across county, payam, and community boundaries, including movements associated with seasonal migration, displacement, access to grazing areas, fishing grounds, agricultural land, markets, and humanitarian support. These movements are influenced by both ecological conditions and administrative jurisdictions, which determine where people can access services, negotiate resource use, and establish temporary or permanent settlements. The

diagrams therefore support the interpretation of mobility patterns discussed in the empirical chapters by showing the institutional landscape within which such movements take place.

These materials are provided as supplementary information rather than as analytical figures because their primary purpose is to assist the reader in understanding the spatial and administrative context of the study sites. They complement the qualitative findings by clarifying the relationship between local governance structures, territorial organization, and flood adaptation strategies among communities living in and around the Sudd wetland.

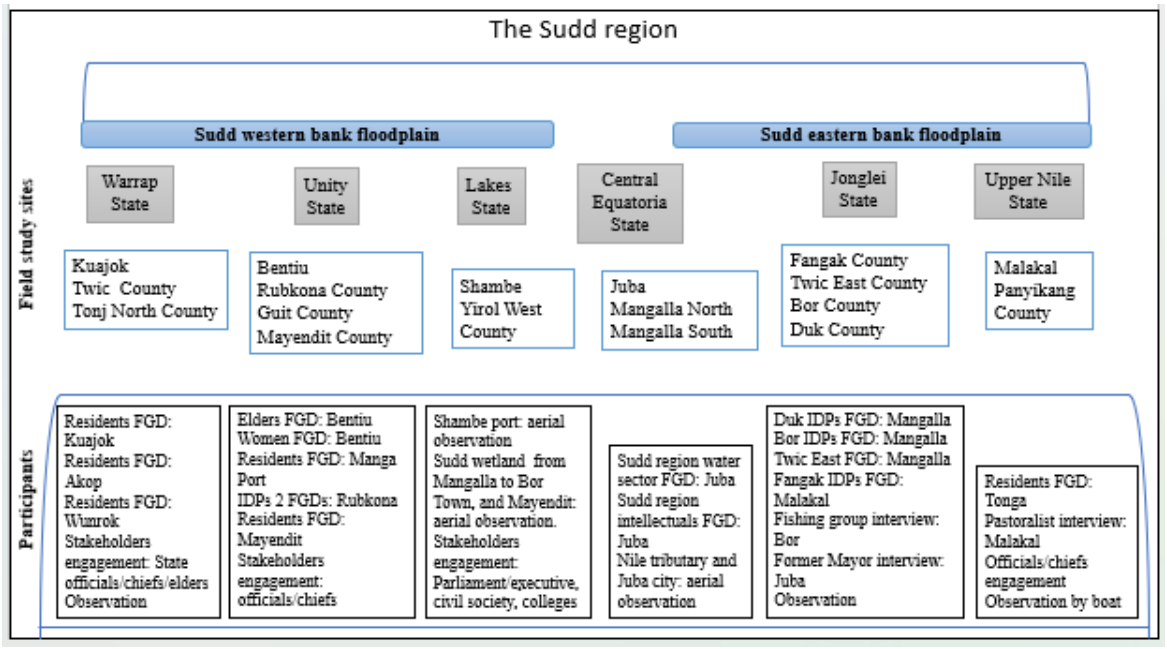


Figure 29: Schematic representation of the study area within the Sudd region.

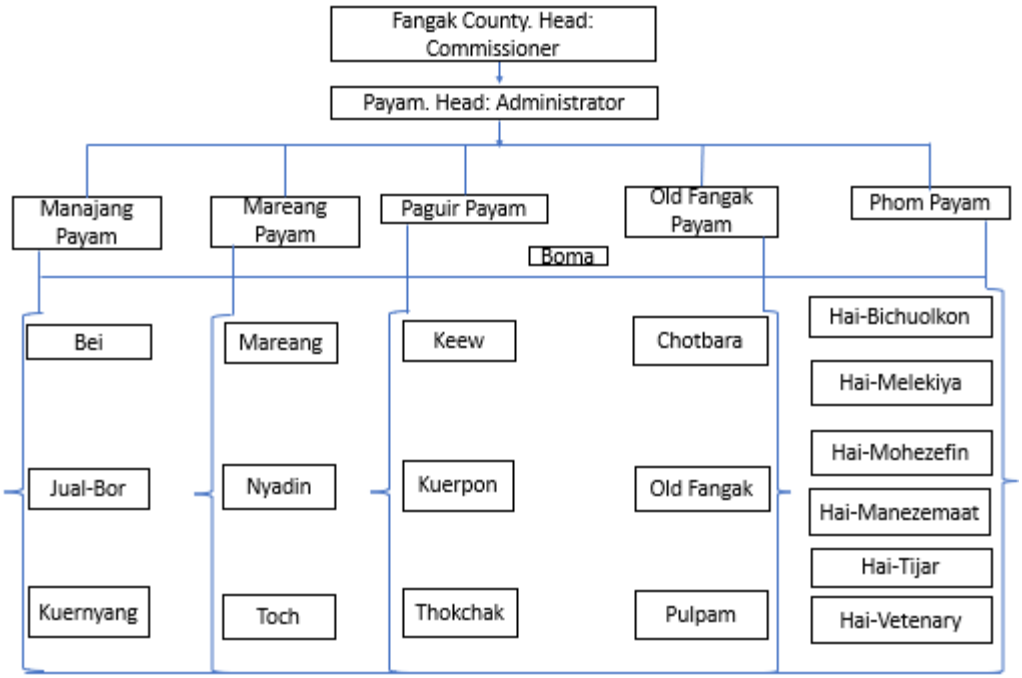


Figure 30: Fangak County (Jonglei State) Administrative structure.

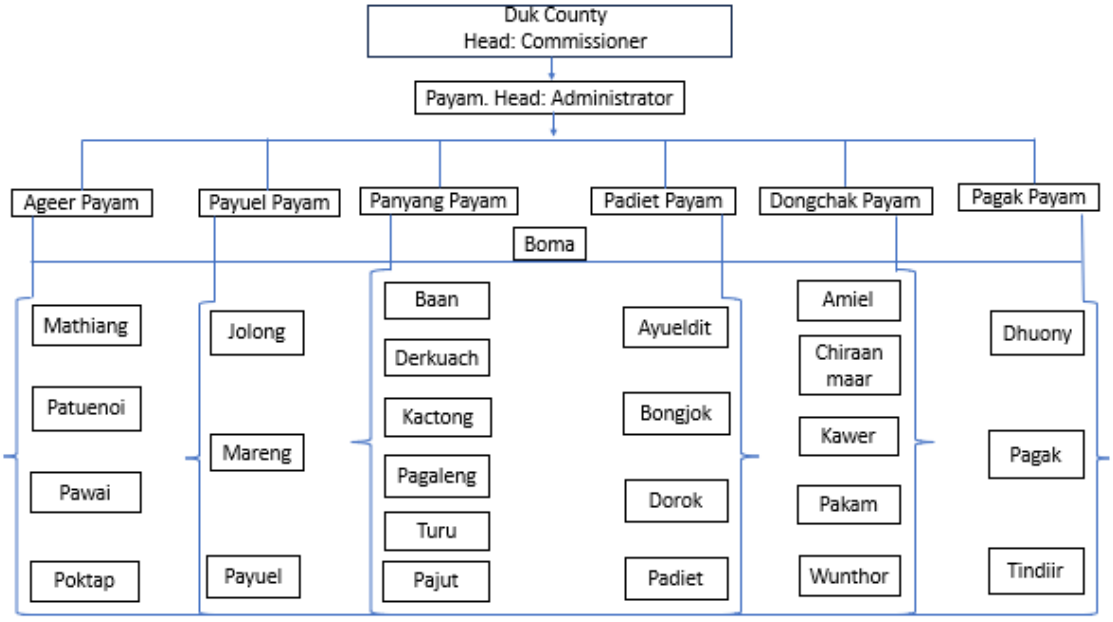


Figure 31: Duk County (Jonglei State) Administrative structure.

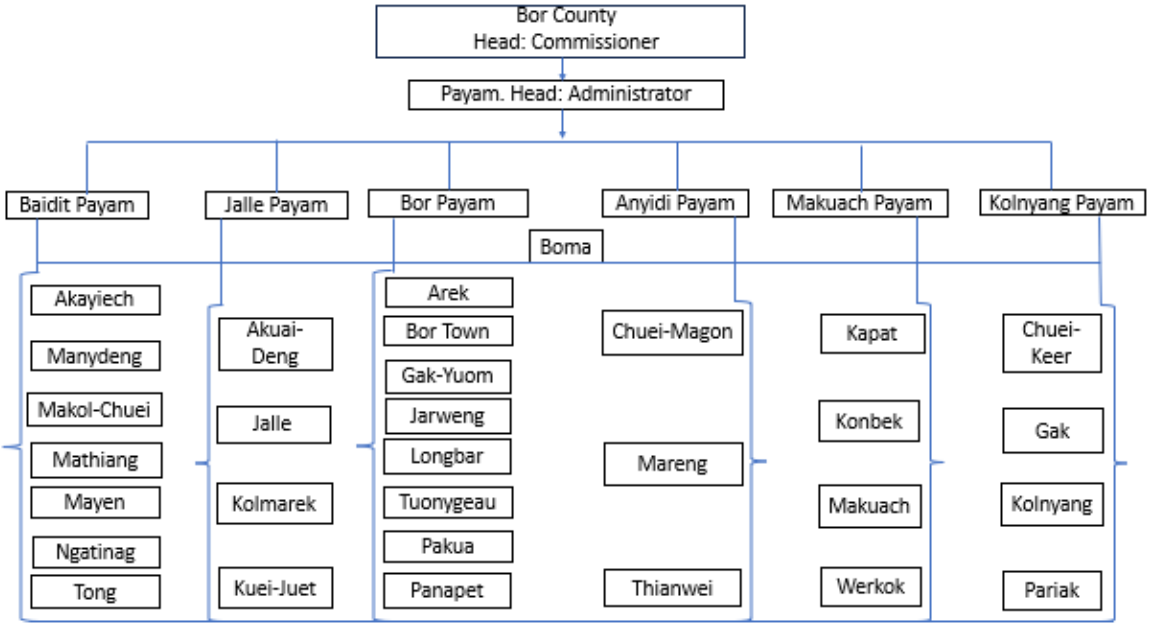


Figure 32: Bor County (Jonglei State) administrative structure.

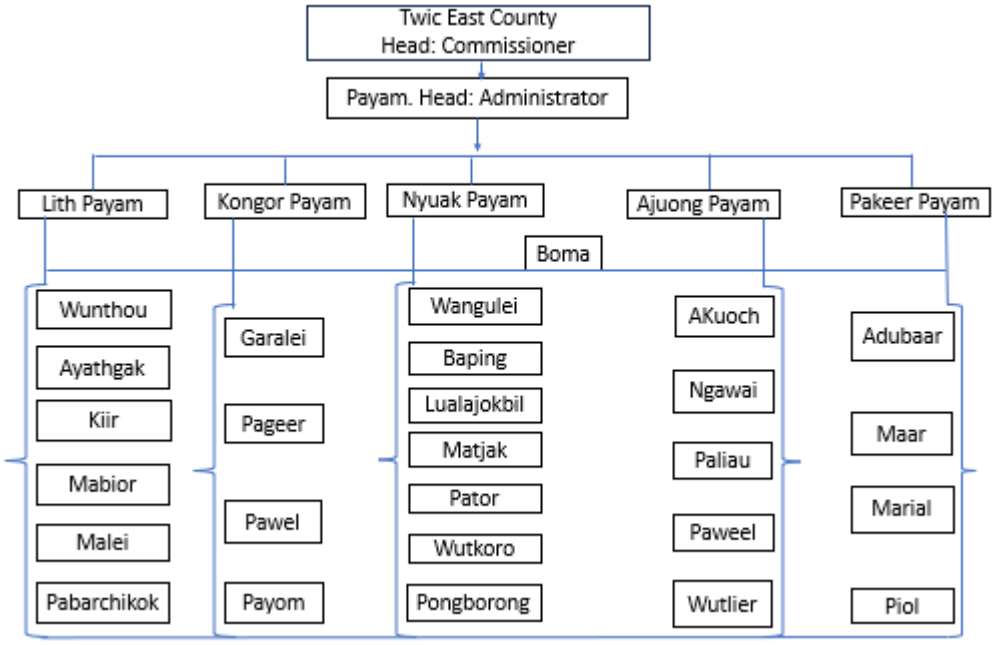


Figure 33: Twi East County (Jonglei State) Administrative Structure.

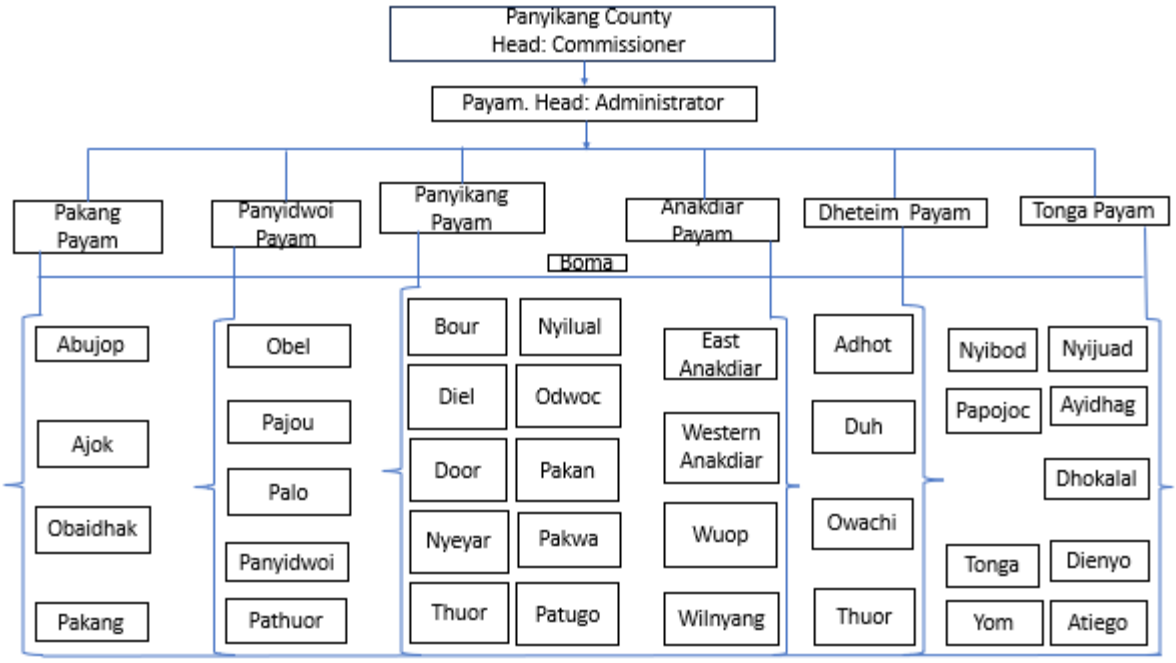


Figure 34: Panyikang County (Upper Nile State) Administrative structure.

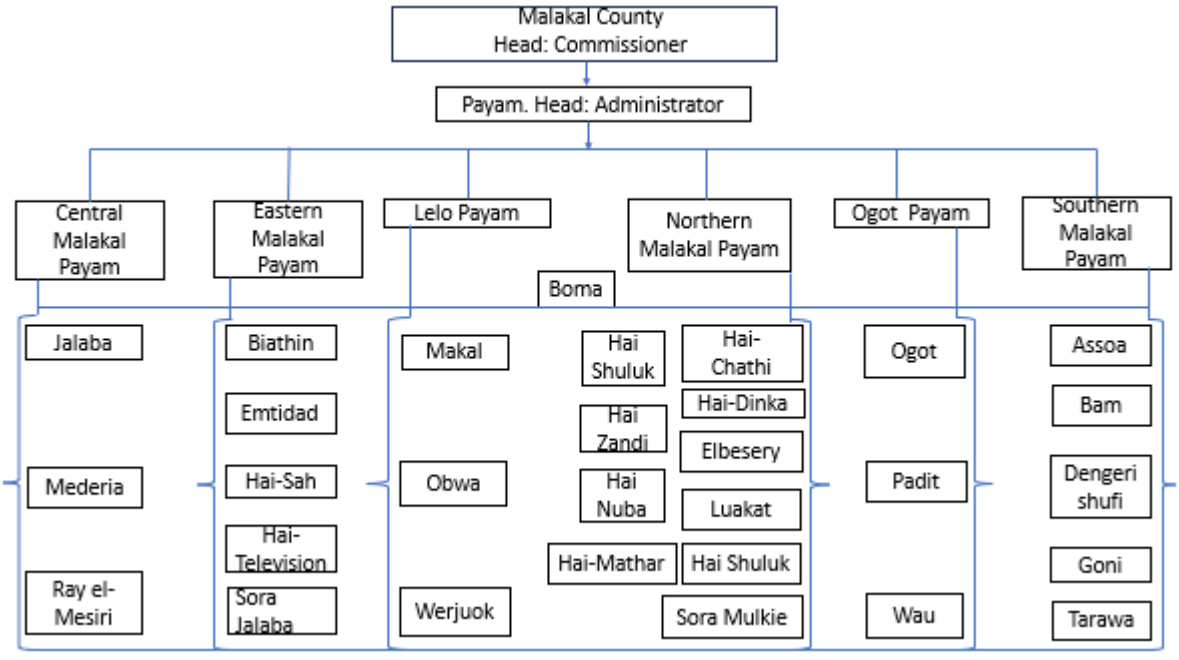


Figure 35: Malakal County (Upper Nile State) Administrative Structure.

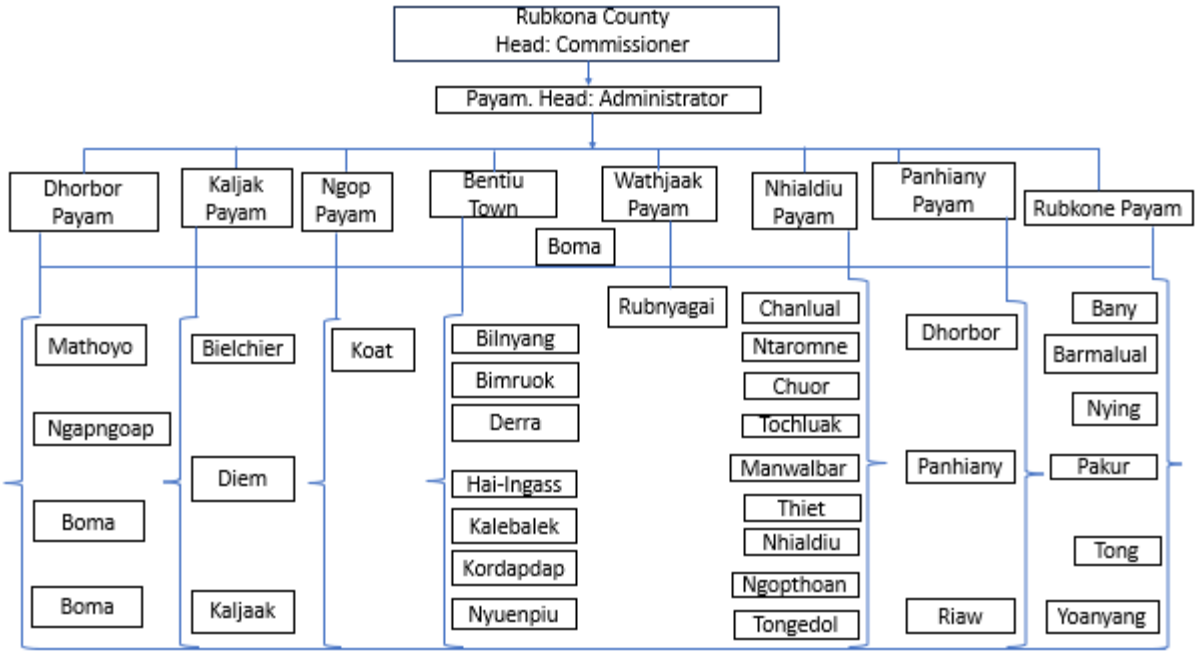


Figure 36: Rubkona County (Unity State) Administrative structure.

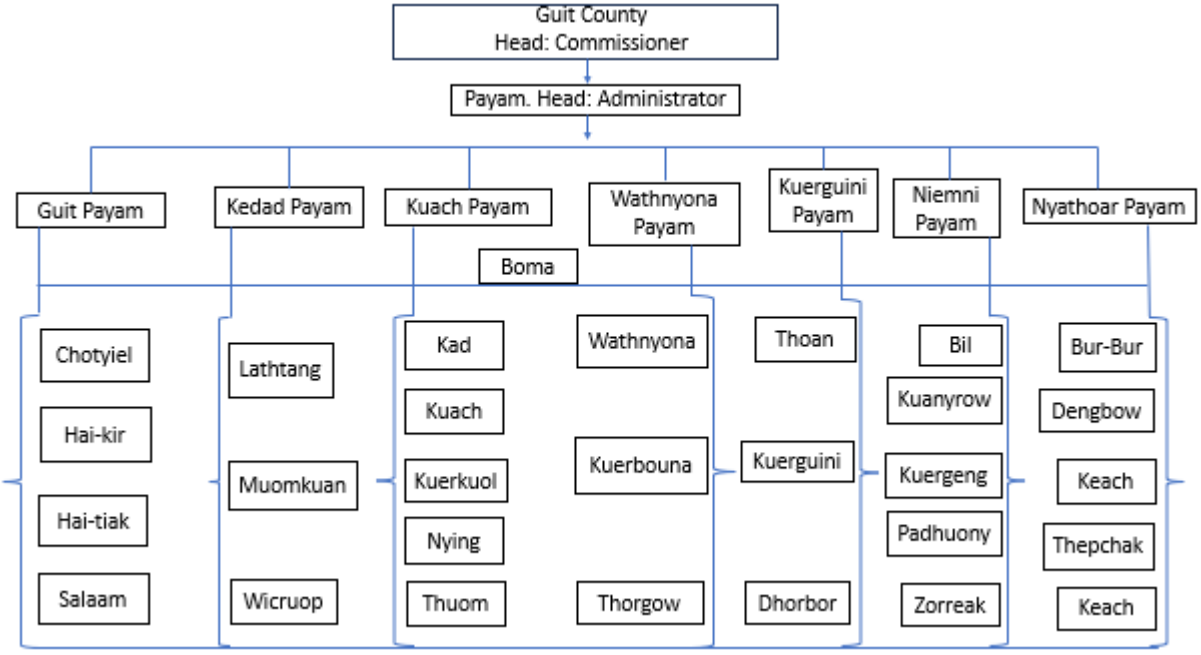


Figure 37: Guit County (Unity State) Administrative structure.

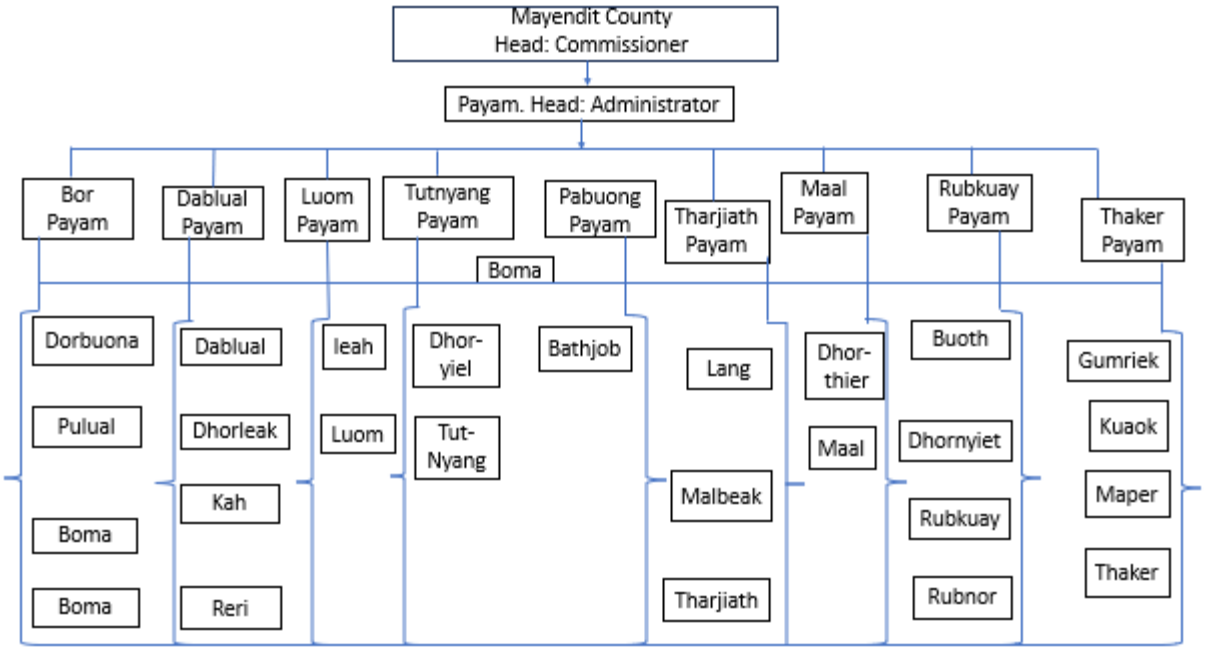


Figure 38: Mayendit County (Unity state) Administrative Structure.

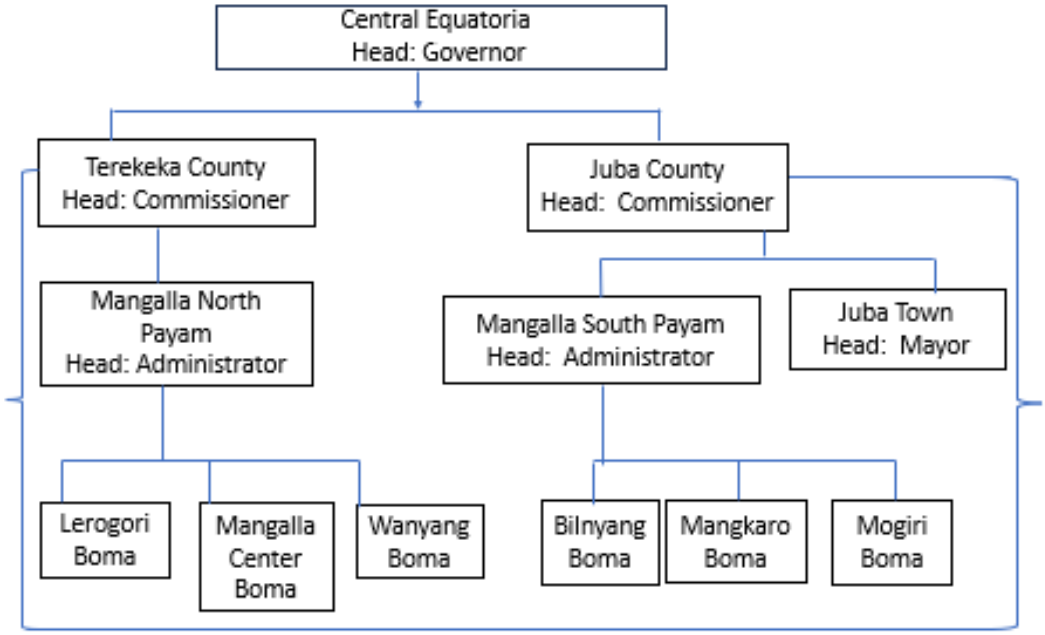


Figure 39: Terekeka County and Juba County (central Equatoria) Administrative Structures.

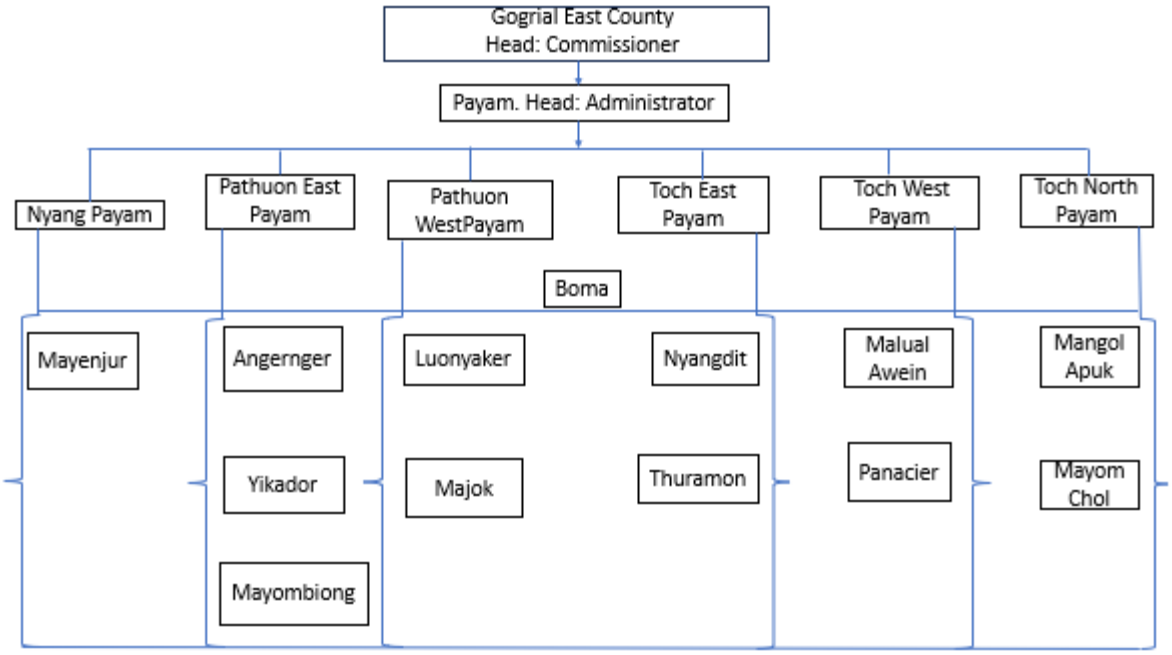


Figure 40: Gogrial County (Warrap State) Administrative Structure.

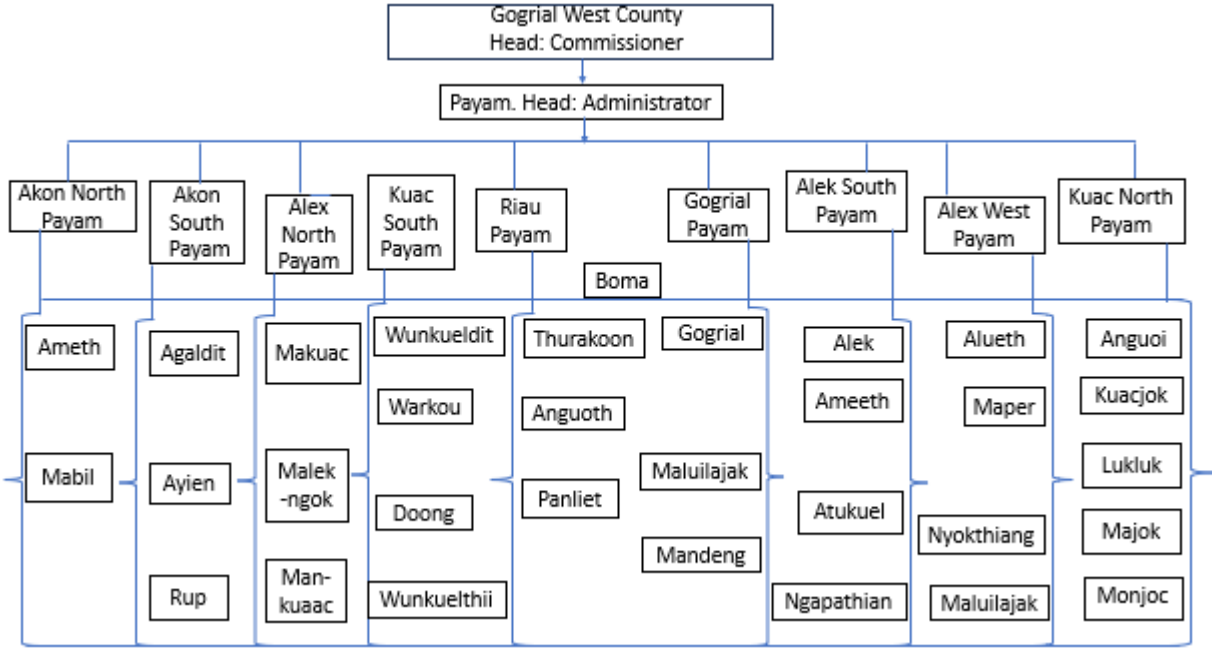


Figure 41: Gogrial West (Warrap state) administrative structure.

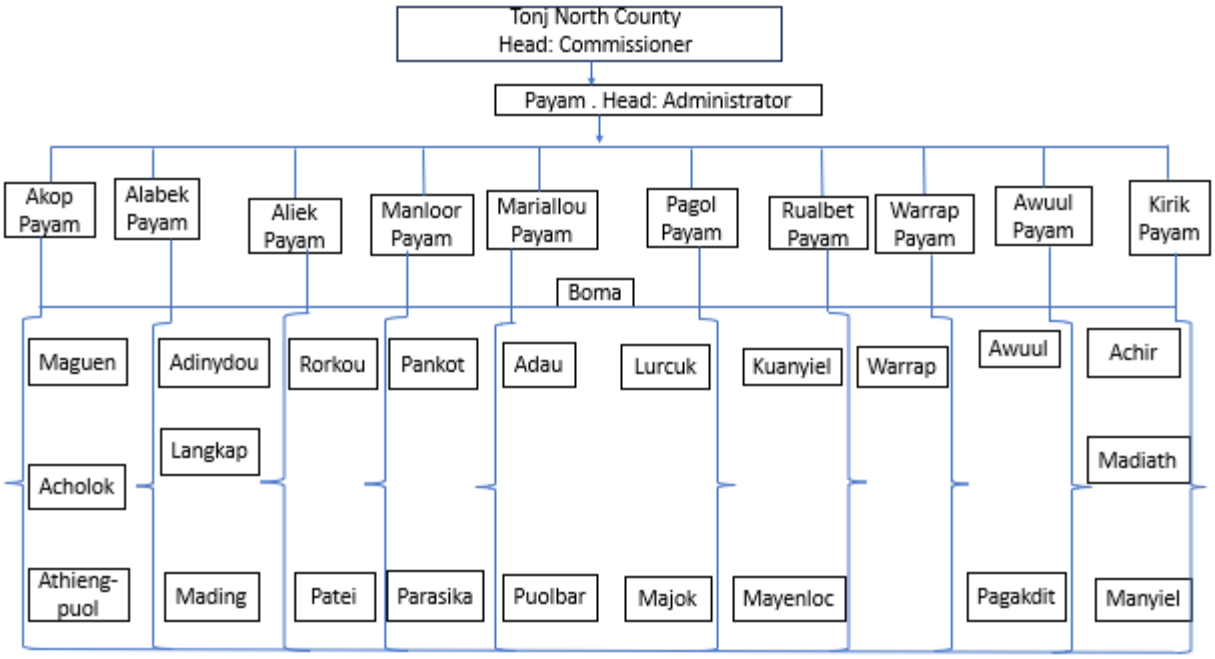


Figure 42: Tonj North County (Warrap State) administrative structure.

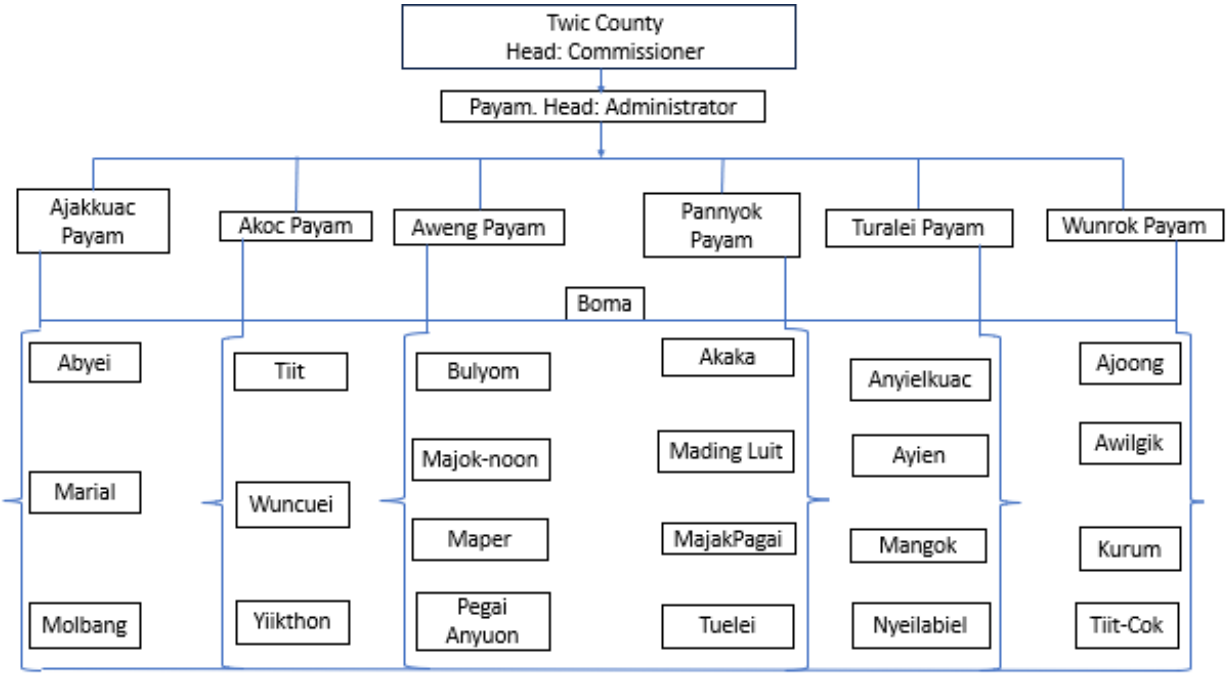


Figure 43: Twic County (Warrap State) administrative structure.



Figure 44: Photos taken during the field study depicting the magnitude of 2019-2024 extreme flooding.

Table 10: Codes structure for the thematic analysis of the field data.

Themes	Files	Code References	Percentage of codes	Rank
Theme # 6 Impacts of flooding on livelihoods	18	738	24%	1
Theme # 10 Extreme flood impacts on migration	18	440	14%	2
Theme # 7 Impacts of flooding on health and wellbeing	18	412	13%	3
Theme # 1 Magnitude of impacts of extreme flooding	18	371	12%	4
Theme # 5 Impacts of flooding on social system	18	339	11%	5
Theme # 2 Local communities' aspirations	18	214	7%	6
Theme # 8 Impacts of extreme flood on women and girls	18	177	6%	7
Theme # 4 Indigenous hydrological knowledge	18	155	5%	8

Theme # 3 Linkage between extreme flood and conflict	18	120	4%	9
Theme # 9 Factors exacerbating flood impacts	18	91	3%	10
Total	18	3057	100%	10

CHAPTER 6

6 IMPACT OF FLOODING ON MIGRATION IN SOUTH SUDAN: A HISTORIC AND CLIMATE CHANGE ASSESSMENT OF THE SUDD

Chapter 6 represents the integrative core of this thesis, moving beyond characterizing flood hazards and exposure to explicitly modelling human behavioral response—migration—under climate stress. The chapter addresses a critical and underexplored question: not simply whether flooding displaces populations in the Sudd, but how migration systems evolve dynamically as flood regimes intensify under climate change. This chapter addresses the third research question: How are dynamic migration patterns influenced by flood extent and how may they change in the context of more severe future flooding? This chapter builds on the previous two chapters by exploring how flooding under future climate influence migration patterns about

some of the most exposed communities to geomorphic hazards (identified in Chapter 6) . The chapter develops field-based decision rules for migration flows, linking them to flood hazard modelling and resultant population exposure scenarios under climate change, before presenting the results and analysis of migration flows, discussions, recommendations for the Sudd region, and conclusion. This is the final substantive chapter of the thesis. This chapter is under review by Climate Risk Management: Climate Risk Management | Journal | ScienceDirect.com by Elsevier. The chapter was co-authored by Jim W. Hall, Kenneth M. Strzepek, Kevin G. Wheeler, and Amelie Paszkowski, who all gave methodological advice, contributed to the conceptualization, and provided feedback on the text and figures.

Supplementary tables follow the reference list of this chapter.

Abstract

Extreme flooding is reshaping migration patterns in the Sudd region of South Sudan, one of the world's largest tropical wetlands and a vital ecological and socio-economic system for agro-pastoral communities. Traditionally, pastoralists depend on seasonal transhumance — cyclical movements between homesteads and floodplains—to access water and pasture. However, unprecedented flooding between 2019 and 2024 has disrupted these long-established practices and heightened regional vulnerabilities. This research integrates qualitative field data with hydrological modeling and climate projections to assess how high-magnitude flood events influence population displacement. Empirical data were collected through interviews, focus group discussions, and participatory mobility mapping with 216 participants across flood-affected communities. These insights informed the specification of migration decision rules reflecting local behavioral responses to flooding. The study then combined these rules with simulated flood scenarios and spatial population exposure data to estimate migration flows under extreme conditions. Findings indicate that large-scale flooding significantly alters both pastoral mobility and broader migration patterns. Under the current 1-in-50-year flood scenario, 60% to 100% of populations in many counties are projected to face inundation, rendering traditional transhumance routes largely unviable. As dry land availability declines, intra-state migration will become increasingly constrained, and consequently, migration patterns are projected to shift toward greater inter-state movement within South Sudan and rising cross-border migration into neighboring countries, including Ethiopia, Kenya, Uganda, Sudan, and the Democratic Republic of Congo. Overall, the results suggest that climate-driven hydrological changes may permanently transform pastoral livelihoods, intensify displacement pressures, and create new socio-economic and political challenges across the region.

6.1 Introduction

Globally, flooding is considered one of the most pervasive climate hazards, causing widespread destruction and, at its worst, forcing people to leave their homes temporarily or permanently (Gillespie et al., 2025). According to the International Organization for Migration (IOM), the environmental drivers of human migration (seasonal or permanent movement of people from one place to another, often across borders or between regions) are often divided into two broad groups: climate events associated with the sudden onset of extreme climate events (typhoons, storms, monsoon floods, glacial lake outbursts, hurricanes, and floods), and climate processes underlying slow and accumulated changes (desertification, land-use processes, food insecurity, sea-level rise, and aridity trends) (Todd-Brown et al., 2014).

The movement of people in response to climate change has been documented (Wolde et al., 2023) with climate anomalies associated with the North Atlantic Oscillation (Drake, 2017), the 'Medieval Warm Period' (10th–12th centuries), extreme climate events in the middle Qing Dynasty (1760–1820) (Li et al., 2017), the modern warm stage (20th century) (Klimenko, 2016) and many other cases.

In recent decades, global environmental changes in the form of gradual and sudden environmental events received wider recognition as a driver of permanent or seasonal internal or cross-border migration (Wolde et al., 2023; de Campos et al., 2018; Groth et al., 2020; Aghazarm and Laczko, 2009).

Almulhim (2024) shows that climate stressors have displaced and profoundly impacted millions of people, resulting in both internal and transboundary migration. While some of the flood affected populations have adopted various strategies to mitigate flood damage, such as resettling away from rivers and enhancing flood protection infrastructure (Wang et al., 2022) other local communities persist in residing within floodplains to exploit valuable resources; the latter case exemplifies the intricate interplay between human proximity to flood-prone areas, for livelihoods and economic need.

An in-depth exploration of pre-modern African society shows that migration is inherent to many cultures (Adeniran, 2020). This is based on the analysis of existing practices throughout the continent. Though colonial regimes in Africa often discouraged cross-border migration, pre-existing cross-cultural interactions sustained cross-border relationships throughout history (Adeniran, 2020). Such cross-border dynamics are observed in South Sudan (the focus for this study), which is a landlocked East-Central African nation that became the world's youngest country on July 9, 2011, following a long struggle for independence from Sudan.

In recent times, migration in South Sudan has also been driven by armed conflict, alongside traditional seasonal migration and the impacts of more extreme flooding. In 2023, 19 % of 12 million total population of South Sudanese fled to neighboring countries, and about 19 % remain internally displaced due to violent conflict throughout the country (UNHCR, 2023). The UNHCR reported that South Sudan is experiencing the largest refugee crisis in Africa and the third-largest refugee crisis in the world. The largest migrant or refugees' populations of South Sudanese are in Uganda, Sudan, and Ethiopia. Kenya's Kakuma refugee camp and its expansion site, Kalobeyei settlement, host more than 148,000 South Sudanese refugees, one of the largest South Sudanese refugee populations in the world (UNHCR, 2023). In 2022, refugees from

South Sudan continued to make up the largest group of returnees in East Africa (Horn of Africa + Great Lakes region) over the last decade, with 151,300 returning primarily from Uganda (77,500), Sudan (49,000), and Ethiopia (23,900).

The outbreak of conflict in Sudan in mid-April 2023 rapidly deteriorated into a severe humanitarian catastrophe, triggering a massive, forced exodus of civilians. Amidst this chaos, the vulnerability of foreign nationals and long-term refugees became acute. In late April 2023, following the outbreak of violence in Sudan, around 46,000 out of 800,000 South Sudanese who continue to live in Sudan after the split of South Sudan were forced to flee back to their homeland due to the devastating humanitarian situation inside Sudan (Wolde et al., 2023). This sudden, uncoordinated repatriation has placed immense strain on South Sudan's already fragile infrastructure and humanitarian resources, particularly in the Sudd region.

The Sudd (Arabic Sadd, "barrier") is Africa's largest tropical wetland and one of the world's largest ecosystems (UNESCO, 2017) of flooded grasslands, shallow lakes, and papyrus swamps, spanning a vast area of the White Nile in South Sudan. The Sudd regulates the hydrology and flow of the Nile, espouses pastoral lifestyles of the local communities, and supports millions of migratory birds and the largest migration of land mammals on Earth (African Parks, 2024; National Geographic, 2025; Neil Lewis, 2024; BBC Earth, 2020; National Geographic, 2025). However, the Sudd region experienced 12 devastating floods in the last 2000 years (Chol et al., 2026) and most recently in 2019–2024, resulting in migration away from the floodwaters. This has been documented in studies that focus on seasonal movement of pastoralists and their herds (transhumance) as they cope with effects of climate variability (Howell, 1988; Evans-Pritchard, 2023; Sutcliffe et al., 1999; de Mabior, 1981) in the Sudd region. Other scholars have studied flood history and its impact on the local population

(Johnson, 1992; Mohamed et al., 2005; Di Vittorio & Georgakakos, 2021). More recently, flood-related migration in the Sudd region has been studied, including records from the IOM (2024), UNHCR (2023), Wolde et al. (2023), and Borgomeo et al. (2023). Chol et al (under review) reports on an extensive field study of adaptation to flooding, finding evidence of how deeply ingrained cross-generational migration routes have been impacted by recent extreme flood events (2019-2024). These flood-induced migration dynamics are exacerbating the vulnerability and fragility of communities across the Sudd region.

However, it remains unclear whether contemporary extreme flood events trigger only transient migration patterns or signify the onset of long-term migratory trends in the Sudd region. This study addresses this principal question: How are dynamic migration patterns influenced by flood extent and how may they change in the context of more severe future flooding? The study therefore seeks to characterize the impacts of extreme flooding on mobility dynamics and migration patterns within the Sudd region. The study first explores changes in seasonal transhumance patterns and population migration in the Sudd region as driven by the most recent extreme variability (2019-2024). Subsequently, this baseline understanding combined with modeling of projected future changes to extreme flood extent and their impact on future migration flows in the Sudd region.

6.2 Study area

6.2.1 Background of the study area

South Sudan contains the world's largest contiguous wetland area, composed of the White Nile/ Bahr el Jebel and the surrounding marshlands along its banks. Together, these are known as the Sudd (Figure 44), which experiences annual seasonal flooding (Easton-Calabria, 2025).

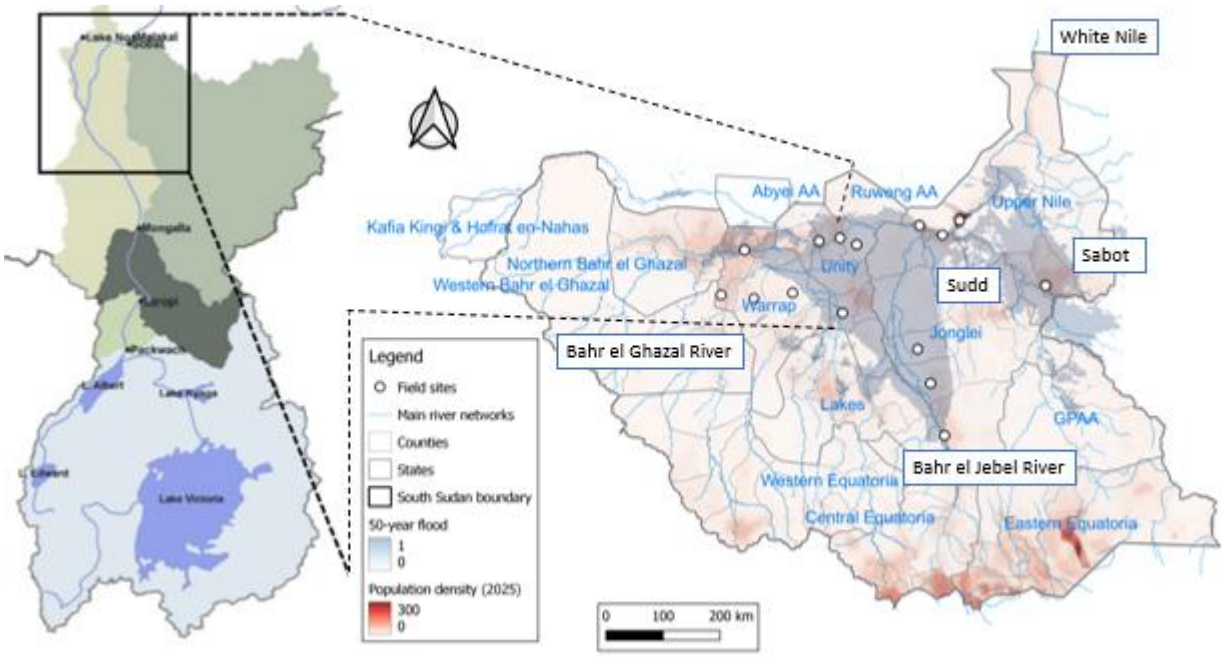


Figure 45: River Nile sub-systems in South Sudan. The figure depicts population density (Wang et al. 2022) in the background, and 100-year return period flood hazards (World Bank, 2026), with the blue scale depicting flood extent. The fading boundary lines represent 79 counties across the country. This figure is based on GPS longitude and latitude coordinates acquired during the field study in the Sudd region. Ruweng AA = Ruweng Administrative Area, GPAA = Greater Pibor Administrative Area, and Abyei Administrative Area.

The size of the Sudd varies as it is defined differently in the literature (Chol et al., 2026). For this research, the Sudd region is defined broadly as the extended Sudd, a combination of the wetlands of the Bahr el Jebel (BJ, most often defined as the Sudd), the Bahr el Ghazal (BG), and the Sobat (SB).

Flooding in the Sudd occurs from a combination of hydrological conditions:

a) Inflows from the upstream equatorial lakes, including Lake Victoria, Lake Kyoga, Lake Edward and Lake Albert, all located within the Nile River Basin. The flows resulting from these lakes have historically been measured at a gauge located at Laropi, shown in Figure 44. These flows have historically accounted for around 90 percent of total inflows to the Bahr el Jebel (Di Vittorio & Georgakakos, 2021)
b) Inflows from the "torrents", which is runoff from seasonal precipitation in northern Uganda and southern South Sudan, entering the White Nile between Laropi and the start of the Sudd wetland at Mongalla. These flows have historically accounted for about 10 percent of total inflows to the Bahr el Jebel (Di Vittorio & Georgakakos, 2021)
c) The extended Sudd wetlands, which include three flooded areas, the Bahr el Ghazal in the west, the Bahr el Jebel in the center, and the Sobat in the east (Figure 44).

6.2.2 Agro-pastoral ethnic communities in the Sudd region

The Sudd is home to agro-pastoral ethnic groups of the Kachipo/Kichepo/Suri (a distinct ethnic group in South Sudan), Jie/Jiye (Nilotic ethnic group residing in the Kassangor Hills), Jur Luo/Luwo (a Nilotic ethnic group), Mundari (a Nilotic ethnic group), Jur Beli (Nilo-Saharan ethnic group), Anuak (a Luo Nilotic ethnic group in South Sudan and Ethiopia), Shilluk/Chollo (a Luo Nilotic ethnic group), Nuer/Naath (a Nilotic ethnic group in South Sudan and Ethiopia), Dinka/Jieng (a Nilotic ethnic), and Murle (a Surmic-speaking ethnic group), often centered around the tributaries of the Nile.

The Dinka, which is the largest group, is spread across Bahr el Ghazal and Upper Nile regions. Several clans of the Dinka groups are in Lakes State, Warrap State, Ruweng Administrative Area, Jonglei State, and Upper Nile State. The Nuer are the second largest, residing mainly in the Greater Upper Nile, Jonglei State, Unity State, and Upper Nile State. The Shilluk are in the Upper Nile State and are found along the Nile and Sobat Rivers, traditionally centered in the Fashoda area, with a unique kingdom history.

6.2.3 Seasonal transhumance (migration) in the Sudd region

These communities have well-established seasonal transhumance routes between highland (settlements/villages) and the intermediate plain (rain-flooded grasslands), lowland (consisting of dense stands of papyrus near toic/permanent swamps), and the Sudd permanent wetland. The seasonal migration originates from the villages, typically located in the highlands on edges of the limit of the seasonal flood extent, at the end of the recession

period and travels towards the Sudd and major Nile River channels. The transhumance routes reverse at the end of dry season and during the inter-season toward the village/settlements. While agro-pastoralism is the main means of subsistence in the Sudd's rural areas, agro-pastoral communities are increasingly exposed to adverse environmental conditions in the Sudd region.

6.2.4 Extreme flood-induced migration dynamics in the Sudd region

The Sudd region suffered from unprecedented flooding between 2019 and 2024, severely impacting seven states and two administrative areas. Consequently, climate-induced migration from rural areas to already inundated urban centers has heightened community vulnerability and regional fragility. Evidence from Bentiu in Unity State and Fangak and Bor in Jonglei State, demonstrates that the depth and extent of flooding in residential areas are unparalleled in living memory (Figure 46). Large swaths of Unity, Jonglei, Upper Nile, and Warrap states were submerged, rendering local populations destitute.



Figure 46: Photographs of the 2020 flood : A) Bor City submerged in flood; B) Villagers navigate a canoe through floodwaters in Bentiu, Unity State; C) Population moving out of the Bor County, Jonglei State; and D) Nyalong Wal, 36, carries her daughter, Nyamal Tuoch, 2, to dry land in a bucket in Fangak, Jonglei State. [Photo (A) by former Mayor of Bor City, Mach Martin Majier; Photo (B) by Medecins Sans Frontieres; Photo (C) by UN Mission in South Sudan; Photo (D) by Peter Caton].

6.3 Materials and methods

This study first delineates migration routes and destinations from current migration practices, including seasonal transhumance and responses to most recent flood extents (2019-2024) in the Sudd region, to establish the baselines for estimating the impact of future flooding on migration flows. Figure 47 presents an overview of data sources used and analytical steps taken, including the development of sets of migration rules and the simulation of population exposures, leading to an estimation of migration flows in the Sudd region.

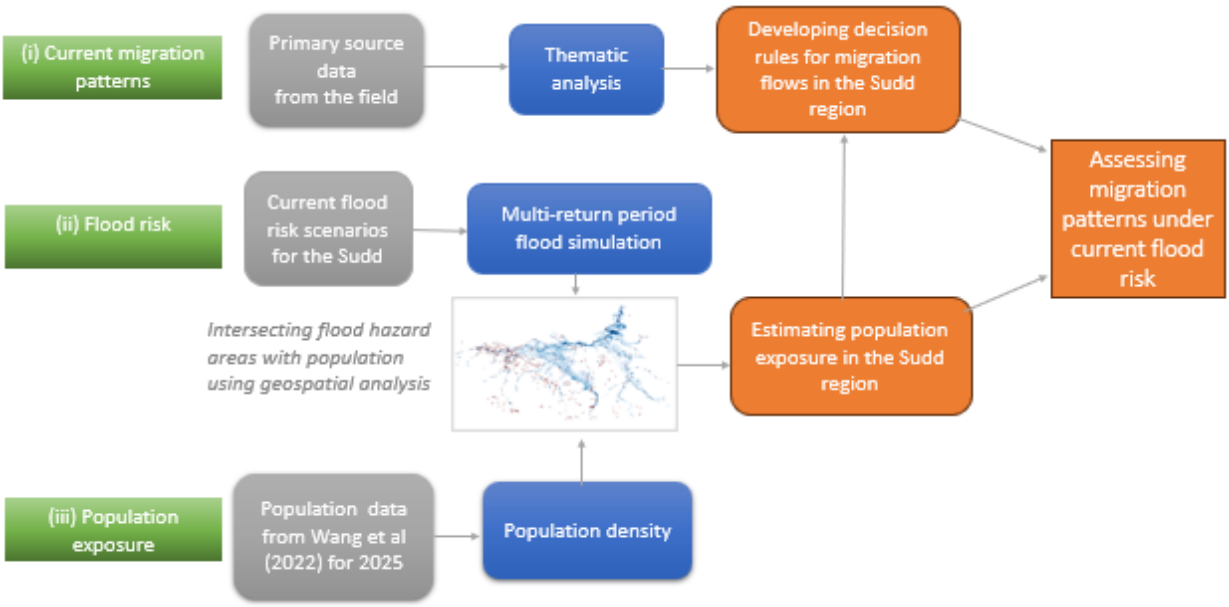


Figure 47: Overview of data used and analytical processes applied.

Data

This study thus combines a range of data sources (Figure 47), including: (i) mapping of population density, (ii) an empirical dataset on current migration and transhumance patterns in the Sudd, collected in 2024, (iii) multi-return period flood inundation model simulations for the Sudd region.

6.3.1 Population mapping

The Sudd suffers from lack of up-to-date census data, so a variety of population estimates from different sources have been evaluated (Chol et al., 2026). This study used georeferenced global population datasets from Wang et al. (2022). These projections were generated using a Random

Forest (RF) algorithm, and the dataset covers 248 countries or areas at 30 arc seconds (approximately 1 km) spatial resolution. This study uses 2025 estimate of spatially distributed population (Figure 44). The study uses exposure scenarios for the communities/counties assessed in the field study and investigates the extent those exposures inform rules that influence migration flows in and out of the Sudd.

6.3.2 Field data on migration patterns

Evidence of migration routes were obtained from a field study conducted by the author between February 18 and June 4, 2024, in counties across five states in the flood-prone areas of the Sudd region (Figure 44). The field visit states include Jonglei, Unity, Upper Nile, Warrap, and Lakes. The specific field sites varied, and included cattle camps, farms, fishing camps, Internally Displaced Persons (IDP) camps, villages, POC sites (a settlement that hosts populations who have been forcibly displaced), and towns. The data were collected from 216 participants who were selected from 15 different ethnic communities and livelihood groups including pastoralists, subsistence farmers, hunters, fishers, and IDPs. While the ethnicity in the Sudd region is dynamic, the data acquired through the field study reflect deep-rooted clan systems, pastoral movements, and socio-economic and political dynamics.

The data on current migration include transcripts from focus group discussions (FGDs) and semi-structured interviews, as well as qualitative mobility mapping data. Most transcripts were recorded in local languages of the participants (eight in Dinka, seven in Nuer, and one in Shilluk). These primary data were collected from the natural settings of the flood-affected

communities and provide both historical and contemporary indigenous memories of the long-established transhumance patterns that are deeply ingrained in the traditional knowledge of the local populations. Furthermore, the data cover lived experiences by the participants in the most recent extreme flooding (2019-2024) and resulting changes in transhumance patterns and population migration responses across the Sudd region. Data from historical flood memories include accounts by the elderly generations that that were used to reconstruct the impacts of the 1930s, 1940s, and 1960s historic flood events, linking those past experiences to contemporary flood-induced migration dynamics.

To obtain information about seasonal transhumance herding customs and practices , the study uses qualitative mobility mapping (citation) by interviewing community-level participants to understand pastoralists' movements, routes, and experiences related to accessibility of water and pastures. Qualitative mobility mapping in transhumance involves using participatory methods, like community-level interviews and map elicitation with herders, to understand their seasonal livestock movements. Group discussions and collaborative mapping sessions were held with 7 to 12 participants across 15 different communities as they drew, sketched, and annotated locations on maps to represent their movements and experiences (Chol et al., 2026). Walking interviews with pastoralists in the cattle camps and along the grazing corridors were also conducted to gain deeper insights into their spatial experiences and interactions with their environments. Herders were asked to mark direction of seasonal migration, encampments and water sources, pasture zones, and areas of potential conflict or cooperation with other communities. In response, herders provided well established seasonal migration patterns based on the seasonality of the Sudd: wet season, recess-season, dry season, inter-season. If ephemeral

ponds are filled with water and pastures are plenty in the wet season, pastoralists move the herds of cattle to their homesteads in land of higher elevation. In the recess season (beginning of the summer), ephemeral ponds/pastures decrease around villages, and pastoralists are prompted to move the cattle to intermediate plains. In the dry season, ephemeral ponds/pastures dry up in the cattle camps sites adjacent to the villages, and pastoralists migrate with cattle to lowlands at the edges of the Sudd. If rain season starts (inter-season) and pastures regrow, pastoralists reverse transhumance movement from the Sudd to intermediate plains towards homesteads/settlement in high land.

Participants were asked to describe and draw qualitative information about changes in routes and destinations of pastoralists' movement across and out of the Sudd region in response to extreme flooding (2019-2024). Participants for each of the 15 communities described new emergent routes from homestead to upland in higher grounds instead of towards the Sudd lowland plains. The pastoralists and the general population migrate away from the Sudd and their settlements to higher grounds inland across and out of the Sudd region.

The study goes beyond GPS tracks to capture cultural values, social relations, resource perceptions (water, pasture), potential conflicts, and historical knowledge embedded in their seasonal migration routes (Umutoni & Ayantunde, 2018; Wikstrøm, 2023) and adds layers of why those routes are chosen (Touréet al., 2019). The FGDs were designed and facilitated to focus on the meaning and perception of seasonal migrations, including herders' subjective experiences, values, and understanding of their environment, beyond objective locations. Participants described social, cultural, and economic factors influencing pastoralists'

movement, such as customary rights, conflicts or relationships with neighboring communities. After transcribing the field data from local languages into English, thematic analysis within NVivo were used s to code and identify themes within text to analyze and understand the data.

6.3.3 Mapping and modelling flood inundation in the Sudd

Several global flood models have previously been used to estimate flood inundation patterns in the Sudd region and have demonstrated sufficient skill for applications in population exposure and migration analysis (Chol et al., 2026). For this study, flood inundation modelling was based on outputs from a recently developed Sudd Hydrologic Model prepared for the World Bank's South Sudan Country Climate Development Report (World Bank Group, 2026). The present study did not independently develop a new hydrological model from raw climate inputs; rather, it used and enhanced the existing modelling framework by integrating the simulated flood outputs with empirically derived migration pathways and mobility rules developed from field research.

The Sudd Hydrologic Model is a process-based water balance modelling framework that represents the major hydrological components controlling inundation dynamics in the Sudd wetland system. The model structure follows the hydrological connectivity of the Nile system, beginning with inflows generated from the Equatorial Nile lakes and tributaries, continuing through the Bahr el Jebel, and accounting for storage and exchange processes within the three major wetland complexes including the Sudd/he Bahr el Jebel, Bahr el Ghazal, and Sobat–Machar Marshes (Figure 44). The model simulates monthly changes in wetland storage and flood extent by accounting for inflows, outflows, precipitation, evaporation, and wetland storage dynamics.

The upstream inflows entering the Sudd were simulated using a combination of hydrological models driven by climate projections. First, the Water Evaluation and Planning (WEAP) model developed for the Uganda Country Climate Development Report (World Bank Group, 2026) was used to estimate future inflows from the Equatorial Nile lakes under alternative climate futures, while accounting for upstream water regulation and changing hydrological conditions. Second, the rainfall–runoff model CLIRUN was applied to estimate runoff contributions from the torrents entering the Bahr el Jebel. CLIRUN converts climate inputs, including precipitation, temperature, and potential evapotranspiration, into river runoff estimates under different future climate scenarios (Strzepek et al., 2011). The analysis was conducted using a monthly timestep to represent seasonal hydrological variability.

The wetland storage and inundation component of the model builds on the foundational water balance approach developed for the Bahr el Jebel by Parks and Sutcliffe (1987). For the Bahr el Ghazal and Sobat–Machar Marshes, the model applies the formulation developed by Yates and Strzepek (1998), which extends the Sutcliffe and Parks approach by estimating monthly wetland storage responses to variations in inflows, outflows, rainfall, and evaporation. These simulated storage changes are then translated into estimates of flooded wetland area under different future climate conditions.

The climate projections used in the hydrological modelling framework represent alternative future climate conditions, including changes in precipitation, temperature, and evapotranspiration that influence inflow and flood dynamics. Rather than using a single deterministic forecast, the model evaluates a range of plausible future hydrological conditions to represent uncertainty associated with climate change. These climate-driven hydrological

simulations provide the basis for estimating potential changes in flood extent and frequency in the Sudd.

The wetland components of the model were calibrated using remotely sensed observations of Sudd flood extent between 2002 and 2022 (Di Vittorio & Georgakakos, 2021; World Bank Group, 2026). Satellite-derived observations were used to constrain the relationship between simulated wetland storage and observed inundation patterns. To estimate spatial flood extent, the modelling framework applies a bootstrapping approach based on historical satellite observations. For flood conditions exceeding the observed range of 2000–2022, a ranked expansion surface method was applied to estimate the likely spatial progression of inundation beyond historical observations (Di Vittorio & Georgakakos, 2021; World Bank Group, 2026).

The resulting flood inundation outputs were then used as spatial inputs for the migration modelling component of this study. The analysis combined simulated flood hazards with empirical observations of migration behavior collected during fieldwork. First, seasonal transhumance routes were overlaid with historically observed flood hazards to examine how pastoral mobility interacts with seasonal inundation patterns. Second, migration responses documented during the 2019–2024 flooding events were characterized using Sankey diagrams to visualize the movement of displaced populations, including migration origins and destinations. These movements were classified into three categories: intra-state migration (movement within a state), inter-state migration (movement across state boundaries), and transboundary migration (movement across national borders).

The empirical migration patterns identified from field research were used to develop migration rules linking flood exposure to mobility responses. These rules were subsequently applied to simulated flood scenarios to explore potential future changes in migration flows. Specifically, migration origins and destinations were overlaid with simulated flood hazards, including a 1-in-50-year flood event, to assess how future flood exposure may alter patterns of movement within and beyond the Sudd region.

Therefore, the modelling approach combined an externally developed hydrological modelling framework with field-based evidence on human mobility. The hydrological model provided physically based estimates of future flood exposure under climate scenarios, while the migration analysis translated these flood scenarios into potential human mobility outcomes based on observed adaptation responses.

6.3.4 Method-estimating population exposure in the Sudd region

Projected georeferenced global population datasets under five shared socioeconomic pathway (SSP) scenarios were obtained from Wang et al. (2022). These projections were generated using a Random Forest (RF) algorithm, and the dataset covers 248 countries or areas at 30 arc seconds (approximately 1 km) spatial resolution, with 5-year intervals for the period 2020–2100. Using Wang et al. (2022) 2025 South Sudan spatially distributed population estimates and spatially distributed flood extent for Sudd from the World Bank (2026), the study estimates the risk of

the population exposed to the maximum flood for a range of return periods. The study uses exposure scenarios for the 15 communities assessed in the field study and investigates the extent those exposures inform rules that influence migration flow in and out of the Sudd. Due to uncertainties in the population dataset, the study uses only the most recent data (2025) derive population exposure scenarios.

6.3.5 Method-developing decision rules for migration flows in the Sudd region.

The study used the data collected in the field to observe how transhumance and population migration patterns play out in regular wet and dry seasons and during extreme flood between 2019 and 2024. Table 11 summarizes how observation from the field during seasonal flooding, as well as during extreme flooding has been captured and used to inform the migration rules for the future. The rules are categorized on the type of migration responses including one rule for intra-state, one rule for inter-state, and one rule for transboundary migration.

Table 11: Sets of predictive rules for migration flows in the sudd region. The rule uses an 'and' logic, requiring a combination of tick-marks for each migration scenario.

Observation from field study	**Rule**	**Intra-state migration**	**Inter-state migration**	**Transboundary migration**

People migrate if exposed to extreme flooding in their area/counties	If >50% of a county's population is exposed to flooding	✓	✓	✓
People migrate within counties, to neighbouring counties, or to neighbouring countries, depending on proximity to higher ground	If <50% population exposure to flooding in adjacent county	✓		
	If >50% population exposure to flooding in adjacent county and <50% exposure in a country in adjacent state		✓	
	If intra- and inter-state migration is impeded due to higher population exposure to flooding			✓
People migrate to areas inhabited by	If destination is inhabited by similar ethnic groups	✓	✓	✓

similar ethnic backgrounds				
People migrate to areas protected by Government/UN services	If destination is protected by Governmental/UN infrastructure	✓	✓	✓
People continue to migrate due to host vs migrant conflict	If conflict arises between host communities and migrants, migration continues		✓	✓
People migrate to established UN IDP/Refugee camps	If there are chain migration networks and perceived quality of UN humanitarian assistance in refugee sites	✓	✓	✓

A rule-based approach was selected for modelling migration responses because it provides an appropriate balance between empirical grounding, contextual specificity, and analytical transparency given the characteristics of the Sudd region.

First, the choice was influenced by data limitations. Reliable longitudinal migration datasets that capture the timing, direction, magnitude, and drivers of mobility in the Sudd are not available, making robust statistical or econometric modelling challenging. The available evidence is primarily derived from field observations, community experiences, and qualitative accounts of mobility patterns, particularly in relation to recent flood events. Therefore, a rule-based approach provides a way to incorporate observed migration behavior into a modelling framework without requiring extensive historical datasets that do not exist.

Second, migration decisions in the Sudd are highly context dependent and shaped by interacting with social, political, and environmental factors. Mobility patterns are influenced not only by flood exposure but also by ethnicity, conflict dynamics, livelihood systems, social networks, access to humanitarian assistance, and the availability of settlement options. These factors are difficult to parameterize adequately within purely statistical models, which may overlook the social processes through which migration decisions are negotiated. The rule-based framework allows these locally specific influences to be represented explicitly by translating field-derived observations into decision rules that reflect how communities respond to changing flood conditions.

Third, the rule-based approach improves transparency and interpretability by making the assumptions underlying migration responses explicit and traceable to empirical evidence. Rather than estimating migration behavior as an unexplained statistical relationship, the framework documents how specific flood conditions and contextual factors influence different forms of mobility, including intra-state, inter-state, and transboundary migration. While more complex approaches, such as agent-based modelling, could further extend this framework by simulating interactions between individual actors and systems over time, the rule-based

approach developed in this study provides an empirically grounded foundation for future formal modelling of climate-induced mobility in the Sudd and similar vulnerable wetland environments.

6.3.6 Method-assessing migration flows under climate change

The Sudd region has historically been devastated by major flood events (Johnson, 1992; Petersen, 2008; Sutcliffe & Brown, 2018; Mohamed et al., 2005; Rebelo et al., 2012, Chol et al, 2026). From the field visits, the study documented historic transhumance and population migration patterns and the changes in response to the recent extreme flooding events (2019-2024) including intra-state, inter-state, and transboundary routes and destinations. Using established migration origins and destinations, the study developed rules to describe the relationship between Sudd flood extent and migration patterns. The migration rules model the influence on choices likely to be taken by migrants from origins to destinations (counties) to characterize migration flows considering a range of return periods for flood events. Lastly, the study then maps migration flows for the three categories of movement, including intra-state, inter-state, and transboundary migration routes, examining their viability under flooding scenarios.

To assess the potential impact of climate change on the feasibility of these routes, the thesis examined these migration routes and destinations under maps of future flood inundation. Then, migration patterns were overlayed with modeled projections of climate change induced flood extent up to for projected return periods for the two eras: 2041-2060 and 2081- 2100.

6.3.7 Assumptions and uncertainties affecting the projection

A key assumption underlying the migration projection exercise is that the empirically derived migration rules adequately represent the dominant mobility responses of flood-affected communities in the Sudd region. Given the absence of reliable longitudinal migration datasets, these rules were developed from qualitative evidence collected during field research rather than from historical statistical migration records. The robustness of the rules is supported through triangulation across multiple sources of evidence, including data collected from 216 participants across 15 communities, representing diverse livelihood groups such as pastoralists, farmers, fishers, and internally displaced populations. Qualitative evidence was generated through multiple methods, including focus group discussions, semi-structured interviews, and participatory mobility mapping.

The resulting rules therefore reflect recurrent patterns of mobility behavior observed across different communities and livelihood systems rather than isolated individual experiences. Furthermore, the identified mobility patterns are consistent with documented migration processes in the wider literature, including seasonal transhumance, displacement linked to environmental stress, and conflict-related mobility. However, these rules remain simplifications of complex human decision-making processes and should be interpreted as scenario-generating tools that represent plausible mobility responses under changing flood conditions rather than deterministic predictions of future migration.

The projection exercise also involves uncertainties associated with both flood modelling and population exposure estimates. Flood-related uncertainty arises from limitations in representing future hydrological conditions, climate variability, and wetland processes. To address this, the analysis uses ensemble-based simulations, including a 30-member weather generator and multiple climate scenarios, to represent a range of possible future conditions rather than relying on a single projection pathway. Flood risk is therefore expressed through probabilistic measures, including return periods and distributions of possible flood extents, allowing the analysis to capture uncertainty in future inundation dynamics. Population exposure estimates also contain uncertainty due to limitations in demographic data availability, particularly the absence of recent census information in South Sudan. To reduce dependence on uncertain absolute population estimates, the analysis focuses primarily on relative exposure thresholds and spatial patterns of exposure rather than precise population counts. The results are therefore interpreted as plausible future scenarios illustrating potential changes in mobility patterns under different flood conditions rather than as forecasts of exact future migration numbers.

Despite these approaches to uncertainty reduction, important limitations remain. These include uncertainty associated with demographic datasets, assumptions embedded within hydrological and exposure models, and the simplification of social decision-making processes into transferable migration rules. The projections should therefore be understood as exploratory assessments of possible climate–mobility futures that highlight potential trajectories of change, rather than predictions of inevitable outcomes.

6.4 Results and analysis

The study first presents findings from mapping the origins and destinations of transhumance patterns and population migration related to the 2019-2024 extreme flood events in the Sudd region, as these act as the baselines for estimating changes in future migration flows. It then discusses the extent of simulated population exposure scenarios to flood risk for the counties in the study area and examines the feasibility of the current routes and migration destinations, before mapping new routes and destinations.

6.4.1 Recent extreme flooding events and current flood risk

World Bank (2025) used a weather generator to simulate a 30-member ensemble of 25 year monthly time series of temperature and precipitation over the Upper Nile Basin including the Sudd. The ensemble was input to the Sudd hydrologic model to generate flood extents at different return periods (Table 12).

Table 12: Flood risk for current climate based on Monte Carlo simulation of 30 -yearly monthly simulations of the Sudd hydrologic model.

Flooded area (km2).	Annual exceedance probability.	Return period (years).
65,000	50%	2
99,000	20%	5
120,000	10%	10

144,000	2%	50
149,000	1%	100

The data obtained for the modelling of extended Sudd provided a cumulative density function for the annual flood extent (Figure 48) which was used to determine the flood extent for any flood return period. The largest annual flood extent observed by remote sensing over the 2019-2024 extreme flood events in the Sudd region was 144,000 km^2 recorded in 2022. Using the CDF estimates, the study maps an exceedance probability of 2 % or a return period of 1-in-50 year flood event.

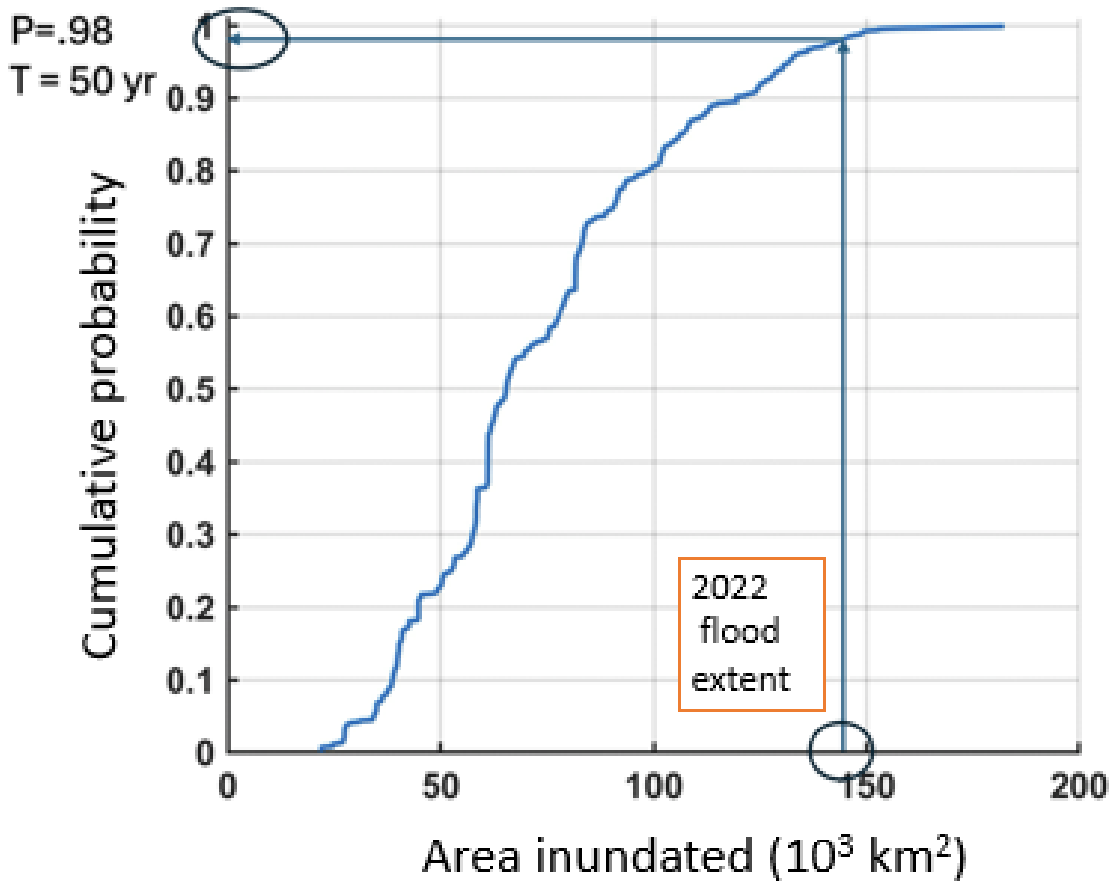


Figure 48: Cumulative distribution function (CDF) of maximum Sudd flood area for (1995-2020). (Data source: World Bank Group, 2026).

Alignment between flood estimates in Chapter 4 and Chapter 6

The flood estimates presented in Chapter 6 should be interpreted in relation to the global flood hazard estimates discussed in Chapter 4. Although both analyses estimate flood extent in the Sudd region, they are based on different modelling approaches and serve different purposes. Chapter 4 evaluated flood extents derived from several Global Flood Models (GFMs), including Aqueduct, CIMA-UNEP, Fathom, JRC, and CaMa-UT, to examine the range of uncertainty in existing global flood hazard products and their suitability for population exposure analysis. In

contrast, the estimates presented in Chapter 6 are derived from a Sudd-specific hydrological modelling framework developed for the World Bank South Sudan Country Climate Development Report (World Bank Group, 2026), which represents the hydrological processes controlling flood dynamics in the Sudd wetland system.

The differences between these estimates are primarily related to model structure and representation of Sudd-specific processes. Most global flood models are designed to estimate flood hazard at large spatial scales and commonly rely on river discharge, flood frequency relationships, and digital elevation models to simulate inundation. While these models successfully identify the Sudd as a major flood-prone landscape, their representation of wetland storage, vegetation dynamics, evaporation, and seasonal floodplain connectivity is often simplified. As discussed in Chapter 4, these processes are particularly important in the Sudd because flooding is not controlled only by peak river discharge but also by the seasonal accumulation and release of water across a highly dynamic wetland landscape.

The Sudd hydrological model used in Chapter 6 explicitly incorporates these processes through a water balance framework that represents inflows, outflows, precipitation, evaporation, wetland storage, and the connectivity between the Bahr el Jebel, Bahr el Ghazal, and Sobat–Machar Marshes systems. The model was calibrated using remotely sensed observations of Sudd flood extent and therefore provides a more process-based representation of wetland inundation dynamics. Consequently, the simulated flood extents from Chapter 6 are generally larger than those estimated by some global flood models presented in Chapter 4.

For example, the global flood models presented in Chapter 4 estimated that 65,000–135,000 km² of the Sudd region could be inundated under approximately 20–25-year return period flood scenarios, depending on the model structure. The Sudd hydrological model used in Chapter 6 estimated a flooded area of approximately 144,000 km² for a 1-in-50-year flood event and approximately 149,000 km² for a 1-in-100-year event. These estimates are within the upper range of the global model estimates, particularly those from models that represent larger floodplain storage areas, such as JRC and CaMa-UT. The differences therefore reflect methodological differences rather than disagreement about the fundamental extent of flooding in the Sudd.

The 2022 flood extent observed through satellite remote sensing provides an additional reference point for comparison. The maximum annual flood extent observed during the 2019–2024 extreme flood period was approximately 144,000 km², which corresponds closely with the 1-in-50-year flood estimate generated by the Sudd hydrological model. This agreement provides confidence that the hydrological model captures the magnitude of recent extreme flooding events. Therefore, while Chapter 4 highlights uncertainty among global flood models, Chapter 6 applies a Sudd-specific hydrological framework that better represents the wetland processes driving flood expansion. The two approaches are therefore complementary. The global flood models provide an assessment of uncertainty and demonstrate the challenges of applying generic flood hazard products in a complex wetland environment, whereas the Sudd hydrological model provides a locally calibrated estimate of flood dynamics used to explore future flood scenarios and their implications for human mobility.

6.4.2 Population exposure to flooding at 50-year return period under in the Sudd region.

As shown in Figure 49, the counties/migration origins in states of Jonglei, Unity, Upper Nile, and Warrap are submerged in observed flood hazard for 2021 (Di Vittorio & Georgakakos, 2021).

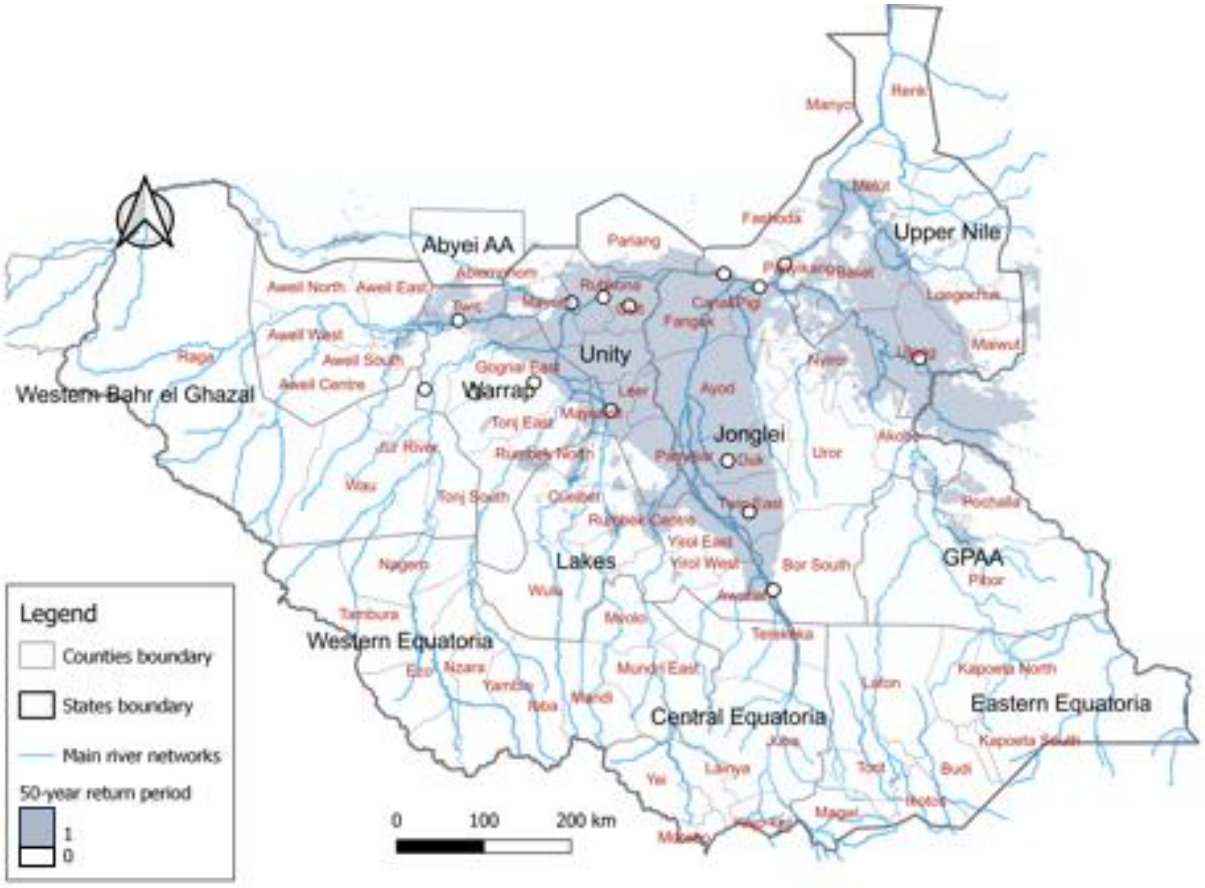


Figure 49: Map of South Sudan's 79 counties. Highlighted areas indicate remote-sensing derived flood extent in the Sudd wetland, primarily affecting Unity, Upper Nile, Jonglei, and Warrap states.

Mapping of population exposure to the 2022 observed flood, which is estimated to be the 50-year flood event, indicates that more than half the population is exposed across most analyzed counties in four states within the Sudd flood plains (Figure 50). In Jonglei State, five of the nine show similar rates (Figure 50A). In Unity State, all seven counties experience significant level of exposure including more than 90% in five of the eight counties (Figure 50B), while in Upper Nile State, Ulang and Luakpiny/Nasir counties experience extreme exposure (80%–100%) (Figure 50C). Lastly, Twic is the only county in Warrap State with a significant (50–70%) exposure rate (Figure 50D).

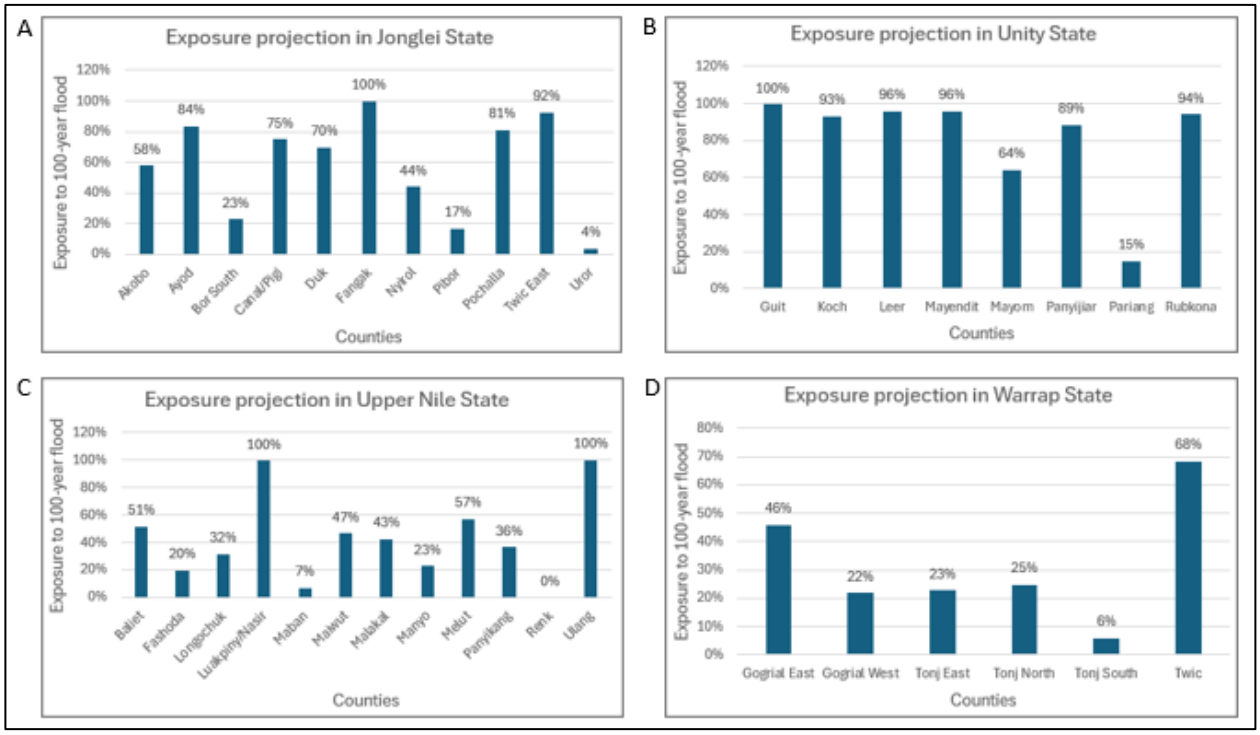


Figure 50: A comparison of exposure rates across 37 counties within four states of South Sudan: Jonglei, Unity, Upper Nile, and Warrap.

6.4.3 Population exposure to extreme flooding in 2019-2024

In 2022, a peak flood extent of 144,000 km² was observed in the Sudd region. Based on the cumulative distribution function (CDF) presented in Figure 48, the 2022 event represents a 50-year return period flood (0.02% probability of exceedance). During this flood, there was a shift toward inland routes that bypass village settlements (Figure 51). Consequently, pastoralists are traversing greater distances with their cattle to forge inter-state connections, such as those extending from Jonglei and Unity States into Lakes, Central Equatoria, Eastern Equatoria, and Warrap States.

Changes in transhumance patterns in response to extreme flooding in 2019-2024

Figure 51 was developed from participatory field-based mapping exercises conducted with pastoralist and other flood-affected communities during the qualitative field research. The pastoralist homesteads (origins of the arrows) shown in the figure were not derived from secondary spatial datasets or external georeferenced records; rather, they were identified by participants during interviews and focus group discussions as representative locations of their counties, payams, and customary areas of residence and seasonal resource use. The mapped points therefore represent community-identified reference locations that helped document perceived mobility routes, changes in transhumance pathways, and relationships between flooding, grazing resources, water availability, and settlement patterns.

The mobility pathways shown in Figure 51 represent participant-described movement patterns and changes in routes over time, rather than precise GPS-tracked migration trajectories. The

figure illustrates how extreme flooding has influenced the timing, direction, and accessibility of pastoral mobility within and beyond the Sudd region. Mobility patterns differed across livelihood groups and population groups, reflecting differences in dependence on livestock, fishing, farming, access to resources, and historical relationships with specific landscapes. Pastoralist groups, for example, primarily described movements associated with livestock grazing, water availability, and flood-driven changes in pasture conditions, while farming and fishing communities highlighted different forms of seasonal adaptation and relocation. These variations demonstrate that mobility in the Sudd is shaped not only by flood dynamics but also by livelihood strategies, social networks, and local ecological knowledge.

The emerging transit patterns (Figure 51) indicate a shift toward inland routes that bypass village settlements. Consequently, pastoralists are traversing greater distances with their cattle to forge inter-state connections, such as those extending from Jonglei and Unity States into Lakes, Central Equatoria, Eastern Equatoria, and Warrap States.

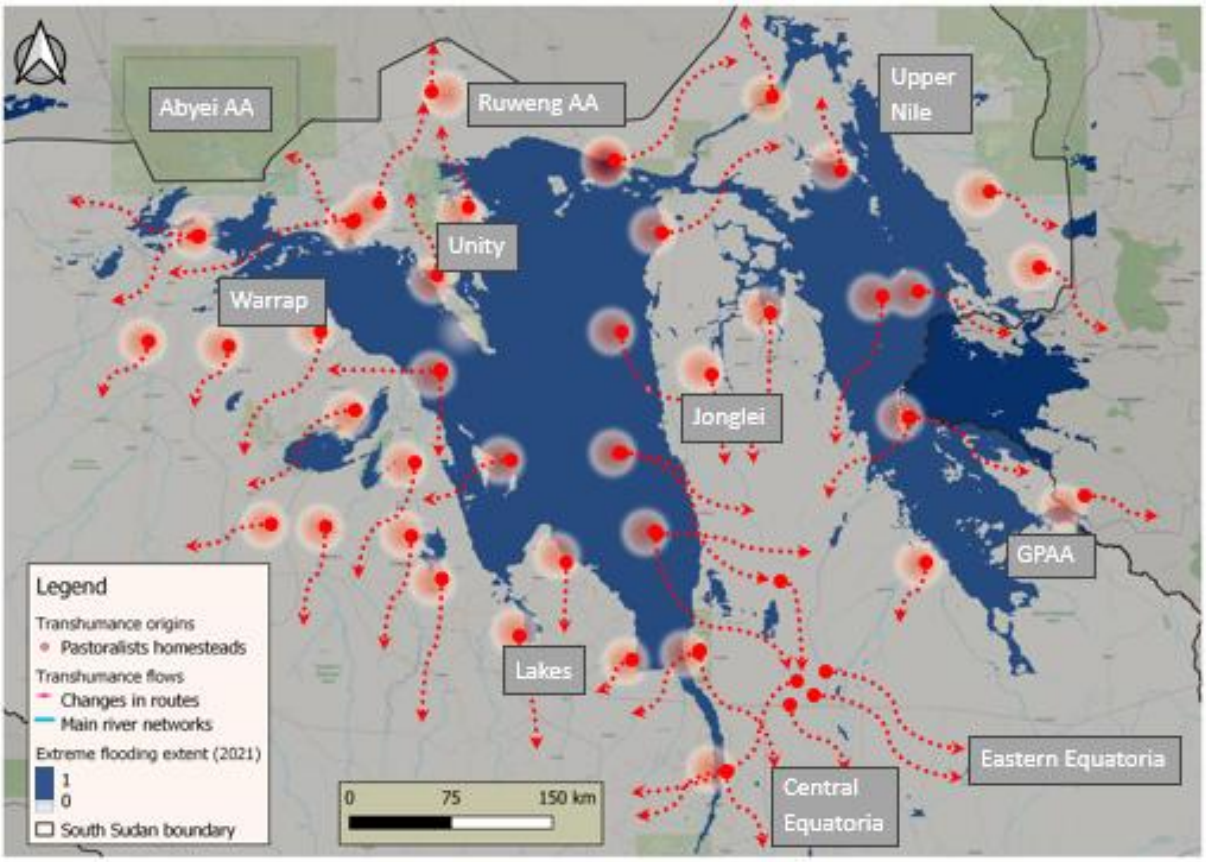


Figure 51: Participatory mapping of pastoralist mobility routes, homesteads, and flood-related changes in transhumance pathways in the Sudd region. Locations and routes are based on community-identified reference points and narratives collected during fieldwork.

Analysis of the qualitative field data shows that these emergent routes that are results of extreme flooding are taken by pastoralists without preparation and with limited knowledge of the potential destinations. The 2019-2024 extreme floods made customary grazing areas and dry season routes inaccessible, forcing spontaneous, unplanned movements away from inundated areas.

Population migration in response to extreme flooding in 2019-2024.

Departing from the analysis of cyclical pastoralist mobility, this section examines broader patterns of population displacement induced by extreme flooding in the Sudd region between 2019 and 2024. Rather than using conventional maps, this section employs Sankey diagrams (Figures 52–54) to visualize the magnitude and direction of reported migration flows. Sankey diagrams are particularly suited to illustrating movement between origins and destinations because they emphasize the volume and connectivity of flows, allowing complex migration pathways to be represented more clearly than static maps.

The migration flows presented in Figures 52–54 were derived from qualitative field data collected through semi-structured interviews and focus group discussions with flood-affected communities across the study sites. These flows represent observed migration movements reported by participants, rather than modelled trajectories or hypothetical pathways. During the participatory mapping exercises, participants identified the locations of their counties and payams as places of origin and described the destinations to which members of their communities, families, or relatives had migrated in response to extreme flooding and the associated disruption of livelihoods.

The Sankey diagrams depict three categories of flood-induced migration: intra-state migration (movement within the same state), inter-state migration (movement between states within South Sudan), and transboundary migration (movement from South Sudan into neighboring countries). Reported destinations include locations where displaced people sought safety, alternative livelihood opportunities, access to essential services, grazing resources, or support from relatives and social networks. Consequently, the Sankey diagrams provide an empirical

representation of flood-induced mobility by illustrating the relationships between reported origin locations and migration destinations.

To interpret the Sankey diagrams (Figures 52–54), the left-hand side displays the reported origins (counties, payams, or states), while the right-hand side shows the reported destinations, whether within the same state, elsewhere in South Sudan, or across international borders. The width of each ribbon is proportional to the relative number of migration movements reported by participants, with wider ribbons indicating more frequently reported migration flows.

Intra-state population migration mapping (2019-2024)

Intra-state migration was significantly high in Upper Nile, with population moving from most exposed counties to less exposed counties such as Malakal. Migration flows among the flood-displaced populations from several counties to Bentiu town, in Unity State, was significantly high, considering perceived UN and Government protection and enclosed dyke construction. In contrast, migration flows among the IDPs from one county to another in Jonglei was very limited, based on the migration rules (52).

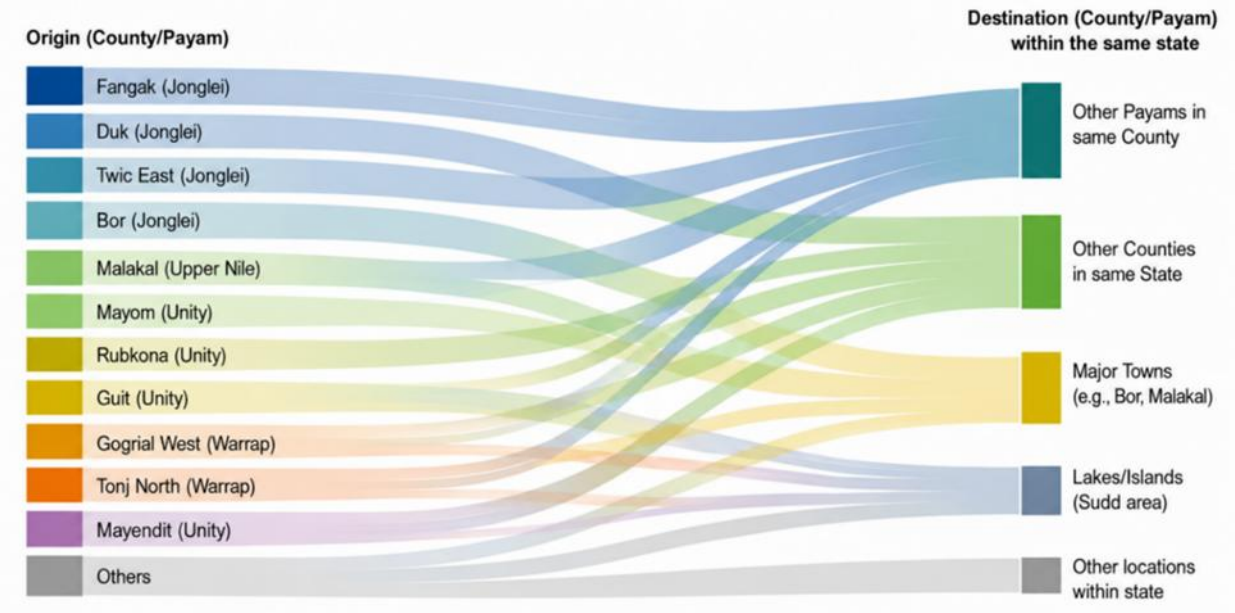


Figure 52: Sankey diagram of reported intra-state flood-induced migration flows (2019–2024). The diagram illustrates migration movements within individual states, linking reported origin counties or payams to their reported destinations. Ribbon widths are proportional to the relative frequency of migration movements reported by participants during qualitative fieldwork.

Inter-state population migration mapping (2019-2024)

Inter-state migration among Internally Displaced Persons (IDPs) was exceptionally high in Jonglei and Unity States (Figure 53). Analysis reveals that populations from Bor, Duk, Fangak, and Twic East counties in Jonglei have primarily fled south toward Lakes (Awerial County), Central Equatoria (Mangalla), and Eastern Equatoria States, while those from Fangak also moved to Malakal in Upper Nile State. In Unity State, displaced populations from southern counties of Mayendit migrated south to Lakes State, whereas those from Mayom and Rubkona sought refuge Twic in Warrap State and in the Abyei and Ruweng Administrative Areas.

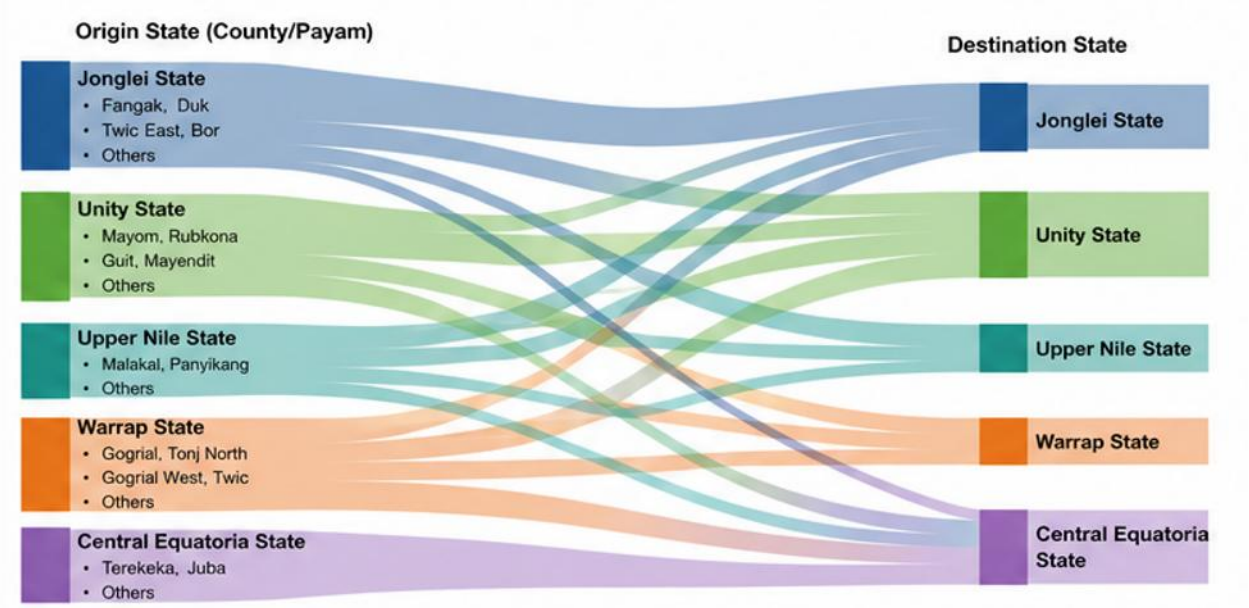


Figure 53: Sankey diagram of reported inter-state flood-induced migration flows (2019–2024). The diagram illustrates migration movements between states in South Sudan, connecting reported origin locations with reported destination states. Ribbon widths indicate the relative frequency of migration movements reported during qualitative interviews and focus group discussions.

Transboundary (cross border) migration mapping (2019-2024)

Between 2019 and 2024, catastrophic flooding in the Sudd region triggered significant cross-border migration into Sudan, Ethiopia, Kenya, Uganda, and the DRC (Figure 54). While international migration rates varied by origin, a major trend involved secondary migration from Jonglei State. Specifically, populations originally displaced from Bor, Duk, and Twic East counties often moved from initial displacement camps to refugee camps in Uganda, Kenya, and the DRC. Furthermore, many individuals from Fangak County moved through Malakal (Upper Nile State) to destinations in Sudan, including the Nuba Mountains and Khartoum. According to field data, Uganda was the primary destination for South Sudanese migrants during this period (Figure 54),

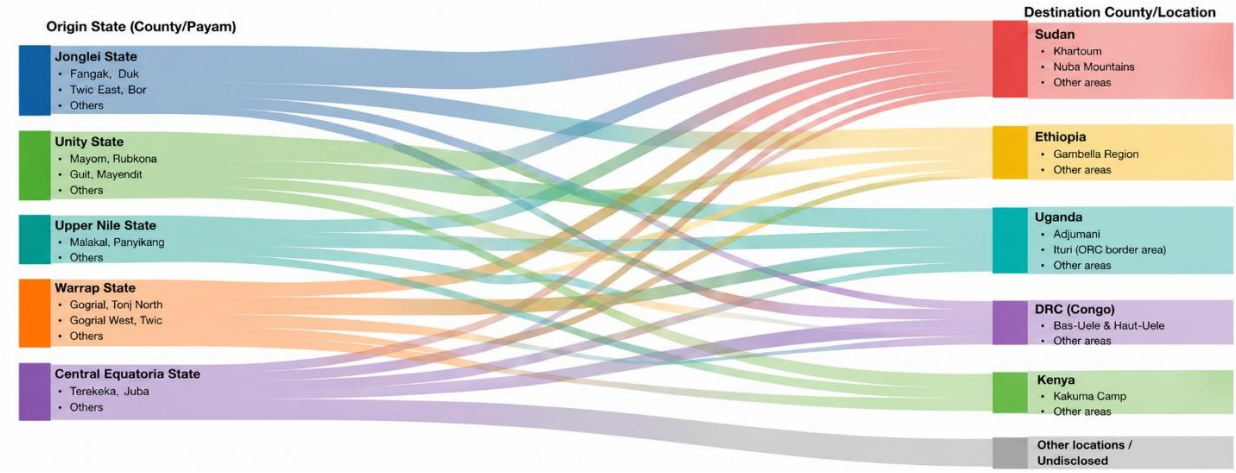


Figure 54: Sankey diagram of reported transboundary flood-induced migration flows (2019–2024). The diagram illustrates reported migration movements from South Sudan to neighboring countries, linking reported origin locations with international destinations. Ribbon widths are proportional to the relative frequency of migration movements reported by participants during qualitative field research.

6.4.4 Flood extent under climate change

To assess the impact of climate change on flood extent, the study used the results of Sudd hydrologic model simulations, combined with future population scenarios from 2025 to 2100. The change in the risk of flood extent across the 55 model simulations is presented in Figure 55.

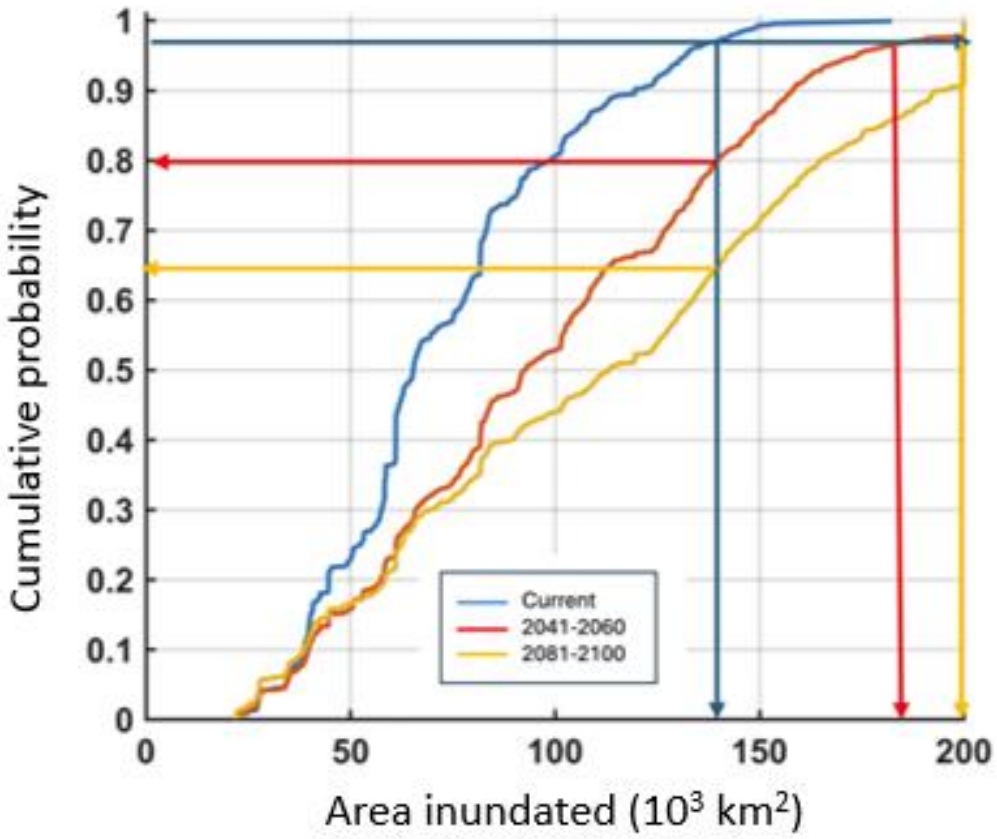


Figure 55: Impact of climate change on the flood extent risk in the sudd region. (Data source: World Bank Group, 2026).

Table 13: Flood risk for future climate change scenario- median change in maximum annual flood for 20-year monthly simulations of the Sudd hydrologic model with inputs from 55 CC Scenario from SSP2-45 and SSP370 for 29 GCMS.

	Current	2040	2090
Flooded area (km2)	Return period (years)	Return period (years)	Return period (years)
65,000	2	1.4	1.4
99,000	5	2.1	1.8

120,000	10	3.0	2.1
144,000	50	5.0	3.0
149,000	100	6.8	3.4

The change in frequency of the 2022 flood, which is the 50-year flood under current climate is projected to increase to be the 5-year flood during the 2 decades surrounding 2050 and the 3-year flood at the end of the century. The magnitude of the 50-year flood is expected to increase from 144,000 km² currently to 180,000 km² in a decade surrounding 2050 and over 200,000 km² at the end of the century.

6.4.5 Assessing migration flows in the Sudd region under climate change

Building on the future flood simulations presented in Figure 55, this section examines how observed migration responses to flooding may evolve under projected climate change conditions in the Sudd region. The analysis overlays empirically documented migration origins with simulated future flood extents to characterize potential migration flows under increasing flood hazard. While the migration origins and destinations are derived from qualitative field data collected during interviews, focus group discussions, and participatory mapping, the flood hazard represents projected inundation under future climate scenarios. This approach links observed behavioral responses to plausible future flood conditions, providing a spatially explicit assessment of how climate change may influence patterns of human mobility.

Drawing on the migration decision rules developed from field observations, the analysis reveals spatial variation in potential migration responses across flood-prone counties in Unity, Jonglei, Upper Nile, and Warrap States. The results are organized into three migration frameworks: intra-state migration (movement within the same state), inter-state migration (movement between states within South Sudan), and transboundary migration (movement from South Sudan into neighboring countries). The mapped destinations represent locations reported by participants in which displaced households or migrating community members sought safety, alternative livelihood opportunities, access to essential services, grazing resources, or support from relatives and social networks.

Unlike the Sankey diagrams presented in the previous section, which were designed to summarize the magnitude and connectivity of reported migration flows, this section presents migration flows as maps because the primary objective is to understand the geographical dimensions of future mobility. Mapping migration flows enables the visualization of migration pathways within their physical and environmental context, showing how future flood extent intersects with settlements, administrative boundaries, river networks, wetlands, and livelihood landscapes across the Sudd region. This spatial perspective is essential for identifying potential migration corridors, destination hotspots, and areas likely to experience increased population pressure under future flooding scenarios. Consequently, the maps provide a more suitable framework for climate adaptation planning, humanitarian preparedness, disaster risk management, and infrastructure and service planning than flow diagrams alone, as they

explicitly reveal where future displacement is most likely to originate and where population movements may concentrate.

Intra-state migration (origins, destinations, and routes) under future climate change

This section assesses the viability of 2019–2024 migration patterns by projecting them against simulated worst flooding exposure scenarios (Figure 55). Results indicate that under these scenarios, seven of the eight counties in Unity State experience little to no intra-state movement, considering significant exposures in almost all the counties in the state. However, adhering to our first rule of migration flows, intra-state chain migration is expected toward Bentiu Town from Rubkona, Guit, and Koch, provide there is a continued presence of UN/State-backed dykes, food aid, and protection for IDPs established during the 2013 conflict and 2019–2024 flooding.

Conversely, significant intra-state migration is expected in Upper Nile, with populations potentially relocating from Ulang and Luakpiny/Nasir to Malakal, Maiwut, and Longochuk. Furthermore, highly exposed populations in Twic County are anticipated to migrate to Gogrial West County in Warrap State. Finally, due to extreme exposure and inter-ethnic conflict throughout Jonglei State, intra-state migration may no longer be a viable survival strategy for migrants from Fangak, Twic East, and Duk counties.

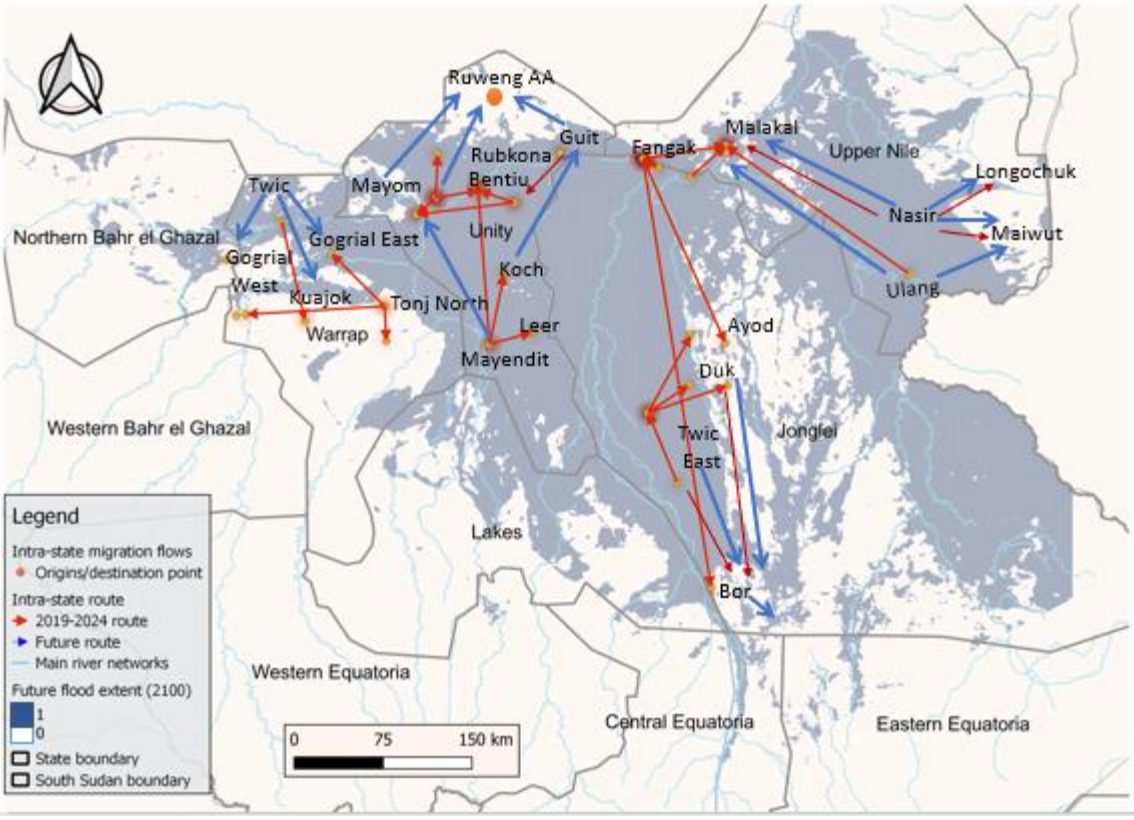


Figure 56: Future mapping of reported intra-state flood-induced migration flows within states and overlaid with 2100 flood extent (World Bank, 2026). Red arrows indicate observed movements described by participants, showing reported origins and destinations of community members affected by flooding between 2019 and 2024. The blue arrows depict future migration flow based on sets of rules acquired from the field visits.

Inter-state migration flows under future climate

Results indicate that most flood-induced inter-state migrants will likely originate from Unity and Jonglei states (Figure 57). Applying the second rule of migration, exposed populations from Unity's Mayendit, Panyijiar, and Leer counties are expected to relocate south ward and upstream to Rumbek East, Yirol East, and Yirol West in Lakes State. Furthermore, increased migration outflows are anticipated from Mayom, Guit, Koch, and Rubkona counties-northward-toward Ruweng Administrative Area, Warrap State, and Abyei Administrative Area.

Inter-state chain migration is anticipated among Dinka populations from Duk, Bor, and Twic East counties (Jonglei State) toward established IDP camps in Awerial County (Lakes State) due to 2019-2024 flooding. Similar migration patterns are expected from these Jonglei counties toward Mangalla/Mongalla Payam in Central Equatoria, and extending further into Eastern and Western Equatoria states, driven by migration chains from both the 1983-2005 war and the 2019-2024 flooding. Additionally, Nuer migration from Fangak County (Jonglei State) is anticipated toward POC sites and IDP camps in Malakal (Upper Nile State), following trends from 2013 war and 2019-2024 flooding.

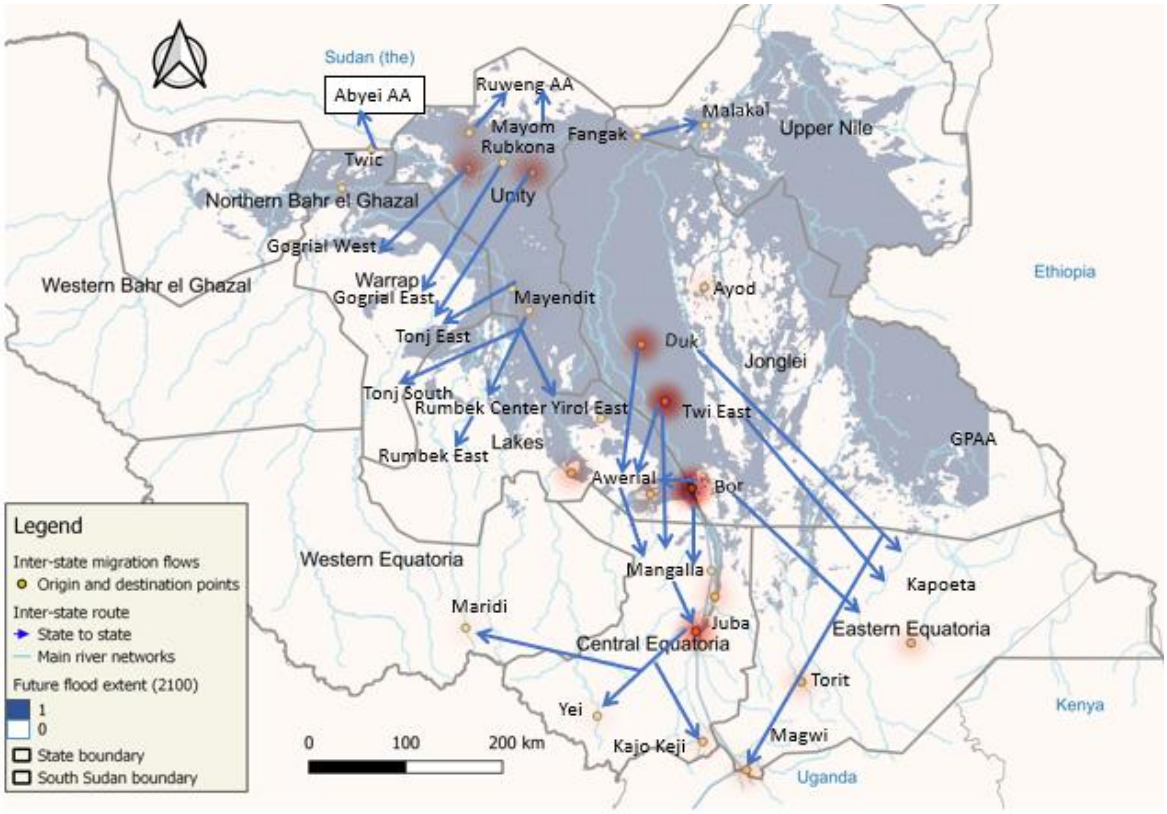


Figure 57: Future mapping of reported inter-state flood-induced migration flows within South Sudan and overlaid with 2100 flood extent (World Bank, 2026). Arrows indicate future movements, based on sets of rules and participants' reports acquired from the field visits.

Transboundary migration flows under future climate

As outlined in our third rule of migration, rising migration in the Sudd region is projected to function as a critical survival strategy, with transboundary movement increasing significantly from Jonglei and Upper Nile States (Figure 58).

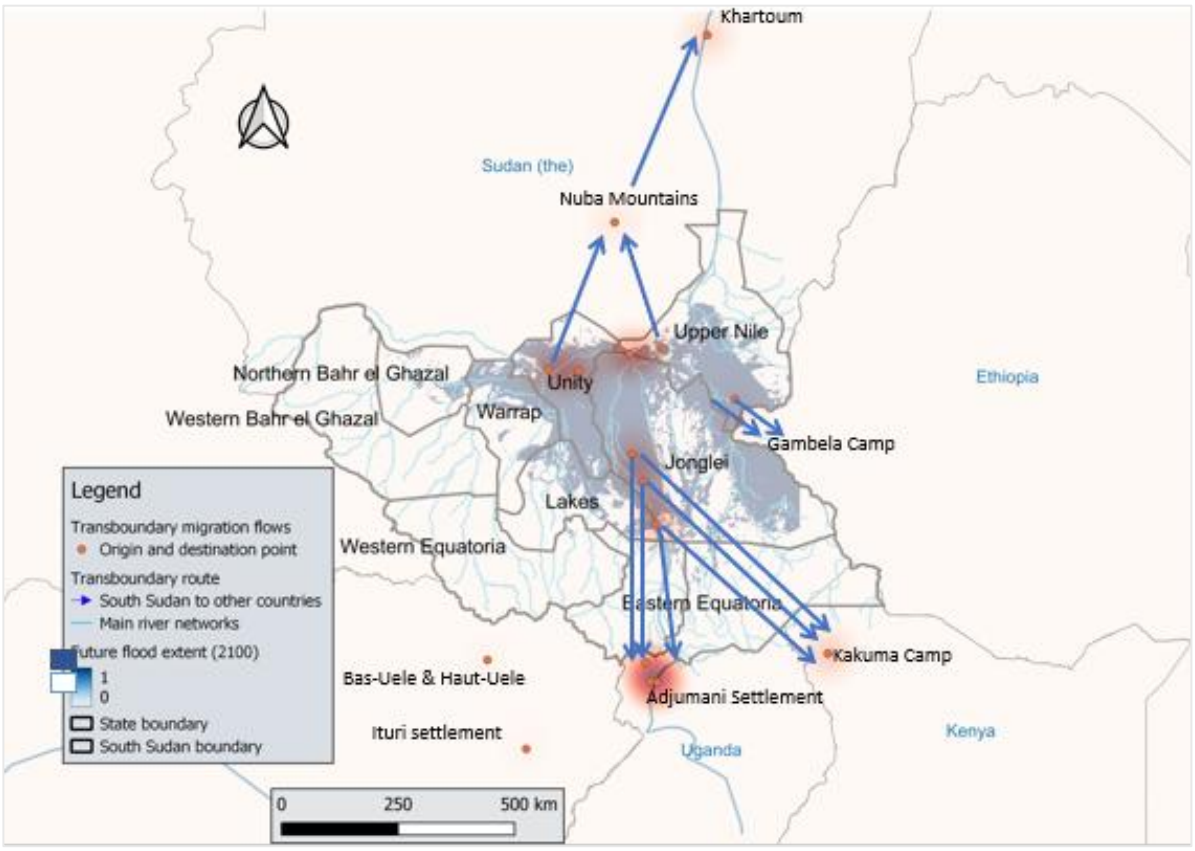


Figure 58: Future mapping of reported transboundary flood-induced migration flows from South Sudan to neighboring countries Future and overlaid with 2100 flood extent (World Bank, 2026). Arrows represent migration pathways reported by participants and sets of decision rules acquired during qualitative field research.

Cross-border migration from Jonglei State is expected to shift towards upstream countries, specifically Uganda, Kenya, and the Democratic Republic of Congo (DRC). Should migrants from Bor, Duk, and Twic counties fail to secure protection or essential services in South Sudan's existing internally displaced person (IDP) camps or regional towns, they are expected to move towards refugee camps via two primary corridors: Juba–Nimule–Uganda and Juba–Torit–Kapoeta–Kenya. Similarly, migration is projected to increase from Nasir/Luakpiny, Ulang, and Maiwut counties in Upper Nile State towards the Gambella Province of Ethiopia (Figure 58).

6.5 Discussion

The discussion explores the implications of key findings, highlighting how climate change threats disrupt deeply ingrained seasonal transhumance routes and trigger increased long-term migration across intra-state, inter-state, and cross-border corridors. These dynamics are consistent with broader evidence that climate variability and extreme events act as key drivers of mobility and livelihood transformation in fragile socio-ecological systems (Raleigh 2011; Thiede, Gray, and Mueller 2016; Caretta et al. 2023; Nabong et al. 2023).

6.5.1 Population exposure scenarios

The projected increasing hazards have serious implications for the survival of local communities, particularly through reductions in land, water, and environmental resources. As the Sudd inundation extent expands under flood amplification scenarios, communities progressively lose land for settlement, agriculture, and cattle grazing. This aligns with long-

established hydrological evidence that the Sudd functions as a highly dynamic floodplain system with strong seasonal and interannual variability in inundation and evaporation (Parks and Sutcliffe 1987; Rebelo, Senay, and McCartney 2012; Sutcliffe and Brown 2018; Mohamed et al. 2005).

As a result, populations lose not only physical assets but also socio-cultural attachments to place, reinforcing findings in political ecology and mobility studies that environmental disruption reshapes both material and identity-based relations to land (Robbins 2012; Sheller and Urry 2006). Using 10-year and 100-year return period simulations, results show significant population exposure, including near-total exposure in several counties within the Sudd region. These findings are consistent with global flood exposure assessments that demonstrate increasing concentration of populations in high-risk floodplains (Jongman, Ward, and Aerts 2012; Smith et al. 2019; Ward et al. 2013; Rentschler, Salhab, and Jafino 2022; Tellman et al. 2021).

Given the limited social and institutional adaptive capacity in the region (Chol et al., 2026), exposure levels between 50% and 100% represent an existential threat to livelihoods and settlement systems. This aligns with resilience theory, which suggests that when exposure exceeds coping thresholds, systems shift from adaptation toward forced transformation or collapse (Walker et al. 2004; Scheffer et al. 2001; Haasnoot et al. 2013).

6.5.2 Mapping migration flows

Migration in the Sudd region under future climate scenarios is highly complex, shaped by hydrological stress, livelihood fragility, and social and political factors. Evidence from field-derived migration rules combined with increasing extreme flood frequency suggests that households in highly exposed counties are likely to adopt migration as a survival strategy.

This is consistent with broader empirical literature showing that climate variability significantly increases mobility, particularly in agrarian and pastoral systems dependent on rainfall and flood cycles (Thiede, Gray, and Mueller 2016; Falco, Galeotti, and Olper 2019; Groth et al. 2020; Wolde, D'Odorico, and Rulli 2023). Migration flows are expected to intensify and diversify into intra-state, inter-state, and cross-border corridors.

These patterns align with the "new mobilities paradigm," which conceptualizes movement as a structural response to systemic environmental and socio-political pressures rather than isolated household decisions (Sheller and Urry 2006; Caretta et al. 2023). In fragile contexts such as South Sudan, mobility is further shaped by conflict dynamics, governance constraints, and uneven territorial control (Henrico and Doboš 2024; Moro et al. 2024; Deng 1998).

While strong kinship networks and cultural attachment to place may moderate out-migration in some cases, they also structure migration pathways and destination choices. However, where exposure thresholds become too high, intra-state migration may be constrained, forcing displacement beyond traditional mobility circuits. This reflects evidence that when environmental stress interacts with insecurity and weak governance, mobility shifts from adaptive circulation to forced displacement (Kälin 2015; McAdam 2009; Nabong et al. 2023).

As inter-state migration toward upstream regions increases, pressure on land, water, and grazing resources may intensify tensions between host communities and migrants. This is consistent with findings that resource competition in environmentally stressed regions can elevate the risk of local conflict (Henrico and Doboš 2024; Moro et al. 2024). Cross-border migration toward Uganda, Kenya, DRC, and Ethiopia is also likely to expand, reinforcing regional-scale displacement corridors driven by climatic stress and livelihood breakdown.

6.5.3 Implication of the findings

Changes in transhumance patterns and routes

The results indicate severe implications for pastoral systems, as deeply embedded seasonal transhumance routes are increasingly disrupted by climate change-induced flooding. These findings align with extensive literature showing that pastoral mobility depends on predictable seasonal access to grazing corridors, water points, and dry-season refugia (Catley, Lind, and Scoones 2013; Fernandez-Gimenez and Le Febre 2006; Umutoni and Ayantunde 2018).

As flood extent expands, traditional corridors, cattle camps, and grazing landscapes in the Sudd may become permanently or seasonally inaccessible. This is consistent with hydrological studies demonstrating increasing variability and persistence of inundation across the Sudd wetland system (Rebelo et al. 2012; Sutcliffe and Brown 2018; Mohamed et al. 2005). Consequently, pastoralists may be forced into longer and less predictable migration routes, potentially shifting toward upland and upstream regions in South Sudan, Uganda, Kenya, and Ethiopia.

Such transitions reflect broader socio-ecological transformation processes in which climate stress disrupts long-standing adaptive systems, forcing structural change in livelihood geography (Pelling 2011; Wise et al. 2014). Increasing dependence on mobility as a coping mechanism also reflects the erosion of locally embedded adaptive capacity under intensifying hydrological extremes (Haasnoot et al. 2013; Scheffer et al. 2001).

Population migration flows in the Sudd region

The findings suggest that climate-driven hydrological change may fundamentally transform settlement patterns and pastoral livelihoods in the Sudd over the long term. Extreme flooding is likely to interact with insecurity, political instability, and economic stress, leading to large-scale displacement and complex migration patterns (Henrico and Doboš 2024; Moro et al. 2024).

Flood-induced migration is likely to be compounded by inter-communal conflict, rising living costs, and constrained access to urban land and services. This reflects evidence that environmental shocks rarely operate in isolation but instead interact with structural vulnerabilities to produce compounded displacement outcomes (Raleigh 2011; Winsemius et al. 2018; Rentschler, Salhab, and Jafino 2022).

While cultural cohesion, kinship systems, and attachment to ancestral land may slow permanent out-migration, they are also likely to channel movement along established ethnic and social networks. However, as intra-state migration becomes constrained in highly exposed counties, populations may be forced into longer-distance displacement trajectories.

Inter-state migration toward upstream regions may intensify tensions over land, water, and grazing resources, potentially increasing conflict risk in receiving areas. This is consistent with evidence that climate-induced migration can exacerbate governance challenges and resource competition in receiving regions when institutional capacity is limited (Kälin 2015; McAdam 2009; Henrico and Doboš 2024).

Cross-border migration into Uganda, Kenya, DRC, and Ethiopia is expected to increase as flood recurrence and magnitude intensify displacement pressures. These dynamics reflect global evidence that climate extremes expand migration corridors and reshape regional mobility systems over time (Thiede, Gray, and Mueller 2016; Caretta et al. 2023; Wolde, D'Odorico, and Rulli 2023).

Importantly, the absence of robust flood management infrastructure in the Sudd region amplifies these risks. Hydrological studies consistently emphasize the need for improved basin-scale water management and adaptive infrastructure to reduce exposure and vulnerability (Parks and Sutcliffe 1987; Rebelo et al. 2012; Sutcliffe and Brown 2018). The field findings further indicate that local communities prefer to remain near water resources but on higher and safer ground, reflecting an aspiration for co-evolution between human settlement systems and dynamic wetland hydrology.

This aligns with socio-hydrological perspectives that emphasize the co-evolution of human and water systems, where long-term sustainability depends on adaptive governance and flexible settlement strategies rather than static control of flood regimes (Sivapalan et al. 2012; Pande and Sivapalan 2017).

6.6 Conclusion

6.6.1 Summary of the findings

This study has examined how dynamic migration patterns are influenced by flood extent and how they may change in the context of more severe future flooding. Migration rules derived from empirical data from field visits, global climate model climate scenarios, and population exposure have been used to characterize migration flows in the Sudd region. Findings from the study reveal that most of the counties in the Sudd region exhibit significant flood exposure under climate scenarios, including those in the states of Unity, Jonglei, Upper Nile, and Warrap. Results show significant population exposure and higher upland migration flow, with higher trends in inter-state and transboundary toward upstream states and upstream countries. Intra-state migration in counties in proximity to the Sudd in states of Unity and Jonglei is projected to become less viable, as displaced persons have dwindling opportunities to find dry land in local areas, while inter-state migration flow is anticipated to increase significantly from these states, along with cross-border migration into Ethiopia, Kenya, Uganda, and the DRC. Destinations within each state are increasingly limited for intra-state migration in some counties in the Sudd region. Consequently, inter-state migration flows is expected to increase among the flood-displaced migrants in all counties in Unity State. Similarly, inter-state migrations increase among migrants from Fangak, Duk, Twic East, and Bor counties in Jonglei State. With increased population exposure and other constraints in migration rules under climate change, cross-border migration flows increase towards upstream countries, with migrants from Duk,

Bor, and Twic East counties in Jonglei State moving to Kenya and Uganda, and migrants from Luakpiny/Nasir and Ulang in Upper Nile state moving to Ethiopia.

6.6.2 Contribution

This chapter makes a methodological and conceptual contribution by developing an integrated approach for understanding climate-induced mobility through the combination of empirical migration evidence, flood exposure modelling, and climate projections. Using field-derived qualitative mobility mapping across 15 communities, the study reconstructs both traditional transhumance systems and recent flood-induced disruptions, translating observed mobility patterns into context-specific decision rules. These rules represent migration as a conditional, spatially explicit, and socially mediated process rather than as a residual outcome of hazard exposure or a purely statistical relationship between environmental change and mobility. By integrating empirically derived migration behavior with hydrological modelling and population exposure scenarios, the chapter enables forward-looking assessments of intra-state, inter-state, and transboundary migration under changing flood regimes.

Furthermore, the findings demonstrate a transition from cyclical and adaptive seasonal mobility toward increasingly constrained, longer-distance, and potentially more permanent migration pathways. The analysis shows that projected changes in flood regimes may exceed local adaptive capacities, reduce the effectiveness of traditional mobility strategies and increase the likelihood of wider regional and cross-border displacement. This chapter therefore provides one of the first integrated assessments linking flood dynamics, human exposure, and empirically

grounded migration responses in the Sudd region. By revealing how climate hazards interact with livelihood systems, social networks, and mobility decisions, the study contributes to broader debates on climate adaptation, conflict-sensitive planning, and humanitarian governance. The findings highlight the need for regional policy frameworks that recognize the evolving nature of transhumance and migration across administrative and national boundaries in East Africa.

6.6.3 Future research

Future research should build on this study, the first to project regional migration flows in and out of the Sudd region under climate change by exploring ways in which the adaptive capacity of the local can be enhanced, via a combination of both hard (e.g., infrastructural) and soft (e.g., anticipatory relocation, awareness campaigns, flood forecasting) solutions. Analysis of empirical data indicates that local communities want to continue to live in proximity with water, but in drier and higher grounds. As the aspirations of the Sudd populations are to stay and flourish in their native land adjacent to the Sudd, adaptive and innovative ways must be implemented for the social system and water system to sustainably co-evolve with neither threatening the other. To meet the aspirations of the local communities and provide an alternative to forced or planned migration, a study on transformative intervention is urgently needed in the Sudd region. Implementation of such transformative strategies fortifies communal capacity to adapt to altered hydrological conditions, effectively reducing climate-induced migration out of the Sudd region.

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6.7 Supplementary Information

This section provides supplementary material that supports and extends the core findings presented in Chapter 6 by offering a more detailed spatial and empirical grounding of the migration and exposure analyses. While the main text synthesizes model outputs and qualitative field evidence to describe broad patterns of flood exposure and mobility transformation, the supplementary figures and tables provide the underlying spatial relationships, origin–destination structures, and seasonal dynamics that inform these interpretations.

The inclusion of this material is important because migration and transhumance in the Sudd are inherently spatial and seasonal processes that cannot be fully understood without explicit reference to location-based evidence. Figures 59 and 60, for example, directly overlay empirically mapped transhumance routes—derived from GPS-based fieldwork and participatory mobility mapping (February–June 2024)—with satellite-derived flood extent data (Di Vittorio and Georgakakos 2021). This integration allows for a clearer visual and analytical understanding of how dry- and wet-season mobility corridors intersect with hydrological hazards, thereby making visible the mechanisms through which climate variability constrains, redirects, or potentially eliminates established pastoral pathways.

Also, Tables 14–16 provide structured origin–destination data for intra-state, inter-state, and transboundary migration flows, including geographic coordinates and classification of population or pastoralist movement types. These datasets are essential for interpreting the Sankey diagrams and migration narratives presented in the main chapter, as they clarify the spatial logic underpinning observed mobility patterns. They highlight the multi-scalar nature of

displacement—from localized intra-county circulation to regional and cross-border movements toward refugee settlements and urban centers. These supplementary materials strengthen the robustness of the analysis by linking qualitative field observations with spatially explicit evidence of how flooding reshapes mobility systems across the Sudd and beyond.

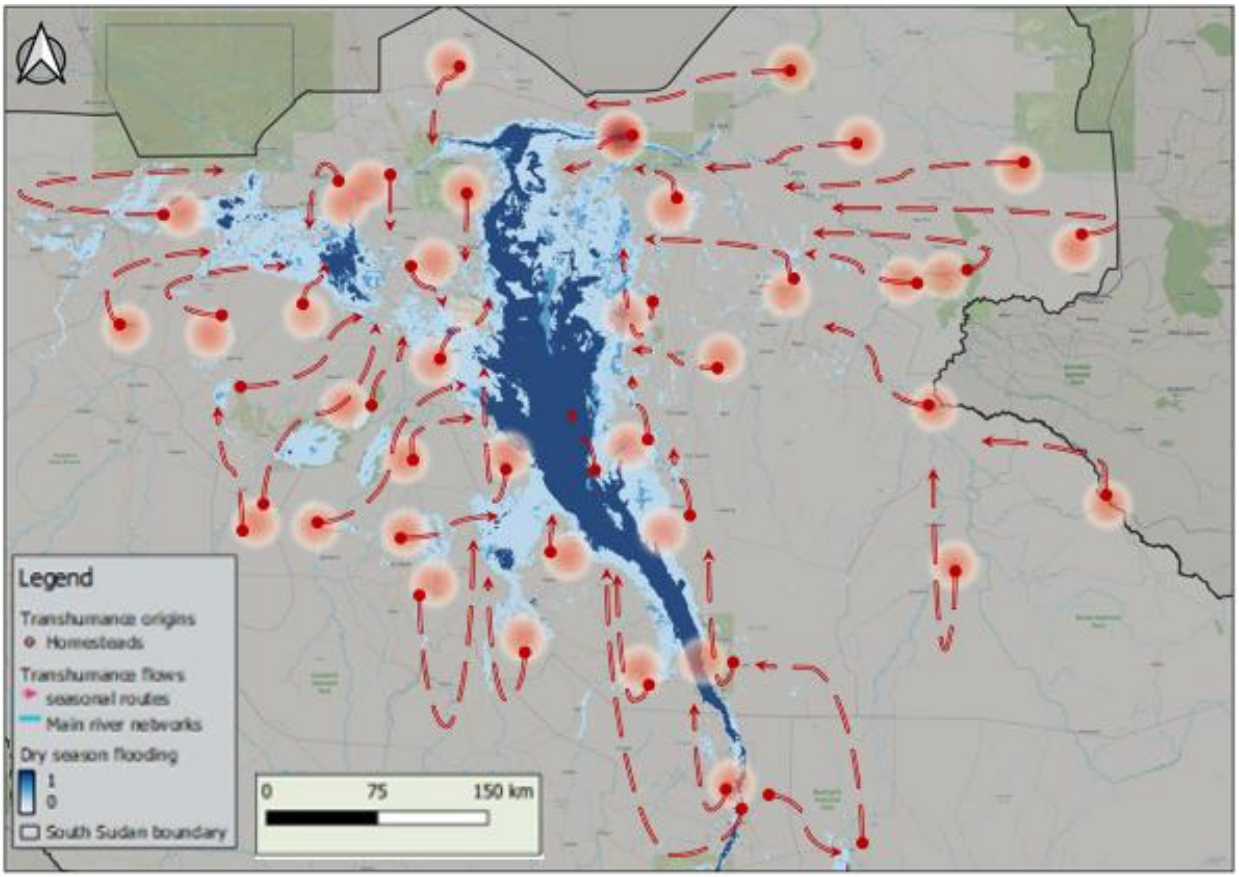


Figure 59: Overlay of transhumance routes between homesteads and the Sudd flood plains during dry season (January to April) with remote sensing derived flood hazard extent (April 2017; Di Vittorio & Georgakakos, 2021). Homestead locations are based on GPS coordinates obtained from the field visits These mappings are based on qualitative mobility mapping from the field visits (Feb- June 2024) to the Sudd region.

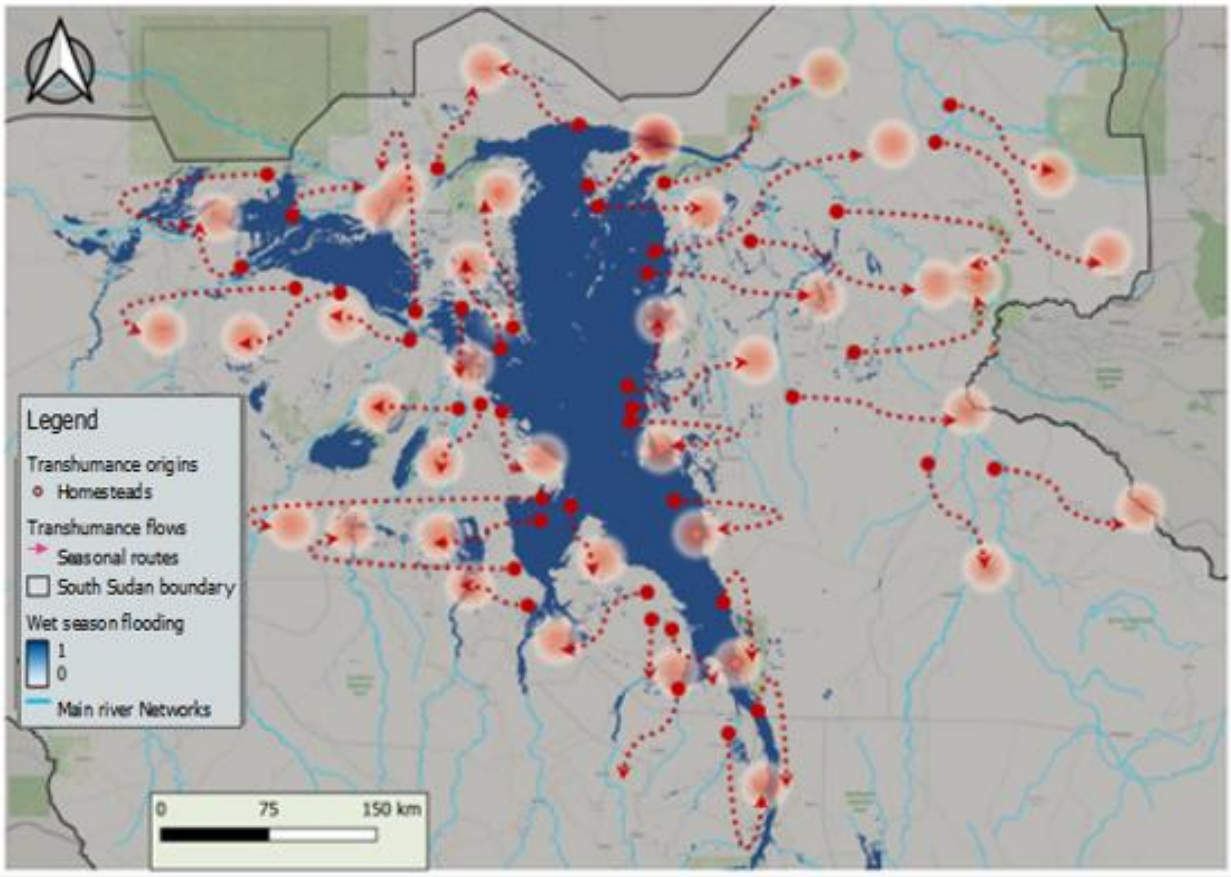


Figure 60: Overlay of transhumance routes during wet season (June-September) and remote sensing derived flood hazard extent for July 2017 (Di Vittorio & Georgakakos, 2021). Homestead locations are based on GPS coordinates obtained from the field visits (February-June 2024) to the Sudd region.

Table 14: Intra-state migration. Dest X Coord and Dest Y Coord, mean destination X coordinates and destination Y coordinates respectively.

Origin/ Counties	Origin X Coord	Origin Y Coord	Routes	Pop/Past	Destination	Dest X Coord	Dest Y Coord
Gogrial West	27.96	8.28	Intra-state	Pastoralists	Bahr el Ghazal Wetland	30.42	9.52
Gogrial East	28.48	8.24	Intra-state	Pastoralists	Bahr el Ghazal Wetland	30.42	9.52
Tonj North	29.08	8.35	Intra-state	Both	Tonj North	29.10	8.09
Tonj North	29.08	8.35	Intra-state	Both	Tonj North	28.03	8.29
Tonj North	29.08	8.35	Intra-state	Both	Tonj North	28.68	8.75
Twic	28.30	8.99	Intra-state	Both	Gogrial East	28.48	8.24

Table 15: Inter-state migration.

Origin Counties	Origin X Coord	Origin Y Coord	Routes	Pop/Past	Destination	Dest X Coord	Dest Y Coord
Rubkona County	29.47	9.17	Inter-state	Both	Ruweng Administrative Area	29.49	9.51
Rubkona County	29.47	9.17	Inter-state	Both	Abyei Administrative Area	28.49	9.84
Rubkona County	29.47	9.17	Inter-state	Both	Yirol West County - Lakes State	30.44	6.35
Rubkona County	29.47	9.17	Inter-state	Population	Uror County - Jonglei State	31.67	8.07
Rubkona County	29.47	9.17	Inter-state	Population	Juba - Central Equatoria State	31.59	4.88
Bentiu	29.80	9.23	Inter-state	Population	Juba	31.59	4.88

					Ruweng		
			Inter-		Administrative		
Guit County	30.07	9.14	state	Both	Area	29.49	9.51
					Yirol West		
			Inter-		County- Lakes		
Guit County	30.07	9.14	state	Both	State	30.44	6.35
					Yirol East		
			Inter-		County - Lakes		
Guit County	30.07	9.14	state	Both	State	30.71	6.85
			Inter-		Uror County -		
Guit County	30.07	9.14	state	Population	Jonglei State	31.67	8.07
			Inter-		Juba - Central		
Guit County	30.07	9.14	state	Population	Equatoria State	31.59	4.88
					Yirol West		
Mayendit			Inter-		County - Lakes		
County	29.8815	8.06248	state	Population	State	30.44	6.35

Table 16: Transboundary migration.

Origin Counties	Origin X Coord	Origin Y Coord	Routes	Pop/Past	Destination	Dest X Coord	Dest Y Coord
Bor County	31.56	6.21	Trans-boundary	Population	Bidi Bidi Refugee Camp-Uganda	31.35	3.53
Bor County	31.56	6.21	Trans-boundary	Population	Palorinya Refugee Camp-Uganda	31.44	3.17
Bor County	31.56	6.21	Trans-boundary	Population	Adjumani Refugee Camp	31.78	3.38
Bor County	31.56	6.21	Trans-boundary	Population	Kakuma Refugee	34.86	3.71

					camp-Kenya Meri Refugee Camp -		
Bor County	31.56	6.21	Trans-boundary	Population	DRC Congo	28.30	3.58
					Ituri Refugee Camp -		
Bor County	31.56	6.21	Trans-boundary	Pastoralists	DRC Congo	29.05	1.88
					Bidi Bidi Refugee		
Twic East County	31.31	7.01	Trans-boundary	Population	Camp-Uganda	31.35	3.53
					Palorinya Refugee		
Twic East County	31.31	7.01	Trans-boundary	Population	Camp-Uganda	31.44	3.17
Twic East County	31.31	7.01	Trans-boundary	Population	Adjumani Refugee	31.78	3.38

					Camp-Uganda Kakuma Refugee camp-Kenya		
Twic East County	31.31	7.01	Trans-boundary	Population		34.86	3.71
					Duk County - Jonglei State		
Twic East County	31.31	7.01	Intra-state	Pastoralists		31.08	7.54
					Bidi Bidi Refugee Camp-Uganda		
Duk County	31.08	7.54	Trans-boundary	Population		31.35	3.53
					Palorinya Refugee Camp-Uganda		
Duk County	31.08	7.54	Trans-boundary	Population		31.44	3.17
					Adjumani Refugee Camp-Uganda		
Duk County	31.08	7.54	Trans-boundary	Population		31.78	3.38

					Kakuma Refugee		
Duk County	31.08	7.54	Trans-boundary	Population	Camp-Kenya	34.86	3.71
Fangak County	31.05	9.47	Trans-boundary	Population	Khartoum-Sudan	32.54	15.60
Fangak County	31.05	9.47	Trans-boundary	Population	Nuba Mountains-Sudan	30.75	12.00
Fangak County	31.05	9.47	Trans-boundary	Population	Bidi Bidi Refugee Camp-Uganda	31.35	3.53
Fangak County	31.05	9.47	Trans-boundary	Population	Palorinya Refugee Camp-Uganda	31.44	3.17
Fangak County	31.05	9.47	Trans-boundary	Population	Adjumani Refugee Camp-Uganda	31.78	3.38

					Kakuma		
					Refugee		
Fangak			Trans-		Camp		
County	31.05	9.47	boundary	Population	Kenya	34.86	3.71

CHAPTER 7

7 DISCUSSION AND CONCLUSION

Following the last three substantive chapters that address the three principal research questions set out in this thesis, the conclusion chapter covers the thesis summary, highlighting the key findings for each of the research questions; the main conceptual contribution, methodological contribution, contextual contribution; context-based policy recommendations and implications for decision-making at various levels, including the Nile Basin region, South Sudan, the Sudd region, and the local community; a reflection on the key limitations and suggestions for future research; and the final concluding remarks.

7.1 Thesis summary and main findings

This thesis spans three long epochs of human-flood interactions in the Sudd region, South Sudan, including past inter-generational flood memory (1820-1990), contemporary human-flood dynamics (2019 to 2024), and projected population exposure coupled with resultant migration flows. Thus, the thesis addresses the dynamics of human exposure to increasing flood risk in the Sudd region. Given low-lying topography and higher population density around the Sudd wetland and along the River Nile major tributaries, communities in the Sudd region are faced with increasing existential threats from extreme fluvial flooding due to heavy rainfalls over the equatorial lake regions. The main findings of this thesis are summarized around three

principal objectives discussed in substantial chapters, including a geospatial analysis of population exposure to flooding in the Sudd region (Chapter 4), dynamics of human adaptation to flood risk in the Sudd wetland (Chapter 5), Impact of future flood exposure on migration flows in the Sudd region, South Sudan. (Chapter 6).

7.1.1 Geospatial analysis of population exposure to flooding in the Sudd region, South Sudan

Results from intersecting global flood model outputs and gridded population datasets indicate that 0.8-2.9 million people are currently exposed to the 100-year return period flood extent, depending on the flood model and population datasets used. Furthermore, aggregated results of the model agreement intercomparison indicate that all five global models agree on key flood-prone areas within and around the Sudd, which is further corroborated with satellite flood observations. Lastly, an intercomparison of the population density and population distribution among the four georeferenced population products demonstrates that WorldPop and GHSL-Pop population distributions better represent the patterns of the Sudd rural settlements that are typically in forms of clusters, observed along the river tributaries and around the Sudd wetland as well as in the Sudd islands.

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

Findings from the field in the Sudd region reveal that unprecedented flooding in the years 2019-2022 had highly disruptive impacts for the local communities. Results from the field study also indicate high perceptions of a shift in the flood regime among the local populations, including the displaced persons and those who are still living amidst the flood in their villages. Furthermore, field observations show an increase in the magnitude and seasonality of the Sudd, with water levels becoming more pronounced and sustaining longer periods of inundation, leading to longer migratory patterns and emergent movements among both the pastoralists and the larger populations. Analysis of the field data demonstrates that pastoral and population migration occurs at multiple levels, including within the state, inter-state, and across international borders, resulting in many flood-prone areas being abandoned. This thesis provides the first conceptualization of the web of interactions among multiple factors and illustrates the interconnectedness between flooding, migration, conflict, and social change among environmental migrants.

7.1.3 Impact of flood risk on migration in South Sudan: a historic and climate change assessment of the Sudd

Results from the analysis of projected flooding scenarios point to greater flood hazards and significant anticipated population exposure in the Sudd region, with an increased average magnitude. Results reveal deeply ingrained seasonal transhumance patterns between homestead

settlements and the Sudd swamps may no longer be practical under future climate. The study shows significant population exposure estimates, ranging from 60 to 100 percent in some of the counties across the Sudd region. Anticipated significant land losses as the Sudd wetland migrates inland, coupled with these extreme exposure scenarios, are leading to increased migration within and out of the Sudd region. Intra-state migration (relocation within a state) is less favorable as displaced persons have fewer opportunities to find dry land in local areas, while inter-state migration flows (relocation from one state to another) are more pronounced as they increase upstream to Lakes State, Central Equatoria State, and Eastern Equatoria State. Under high impact flood exposure scenarios, transboundary/cross-border migration from the Sudd region increases toward upstream countries, including Ethiopia, Kenya, Uganda, and the DRC.

7.2 Research contributions

This thesis contributes to the study of human exposure to flooding in the Sudd region of South Sudan through a combination of conceptual development, contextual analysis, and methodological development.

7.2.1 Conceptual contribution: human-flood dynamics

Chapter 4 of the thesis, a geospatial analysis of population exposure to flooding in the Sudd region, provides the first systematic analysis of population exposure to flooding in the Sudd

region. Findings from this study provide novel insights into flood exposure in South Sudan, to inform flood management decisions and disaster reduction responses in the Sudd region.

Also, a field study on the dynamics of human adaptation to flooding in the Sudd wetlands (Chapter 5), advances a socio-hydrological approach by demonstrating that local communities are an endogenous part of the water cycle, interacting with the system in multiple ways. In the Sudd region, water, environment, and human systems are dynamically interconnected. This complex interconnectedness results in reciprocal processes where changes in the hydrological system influence environmental conditions, which shape the human health and social system whose adopted cultural adaptations further impact the water system and environment, creating spatio-temporal continuous feedback in the socio-hydrological system. Using analysis from the field data derived from a comprehensive field study that was conducted across the Sudd region with diverse ethnic and cultural communities in their natural settings, this thesis advances a conceptual framework. 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.

Lastly, Impact of flood risk on migration in the Sudd region (Chapter 6) produces a unique synthesis from the estimation of migration flows in some of the most vulnerable communities

to flooding in the Sudd region. The study thus provides a first insight into how climate change-induced flood exposure alters cross-generational seasonal migration routes and influences migration flows in the Sudd region. This thesis therefore acts as a first foundational step towards longer-term evidence-based flood risk management in the Sudd region and hopes to contribute towards discovering a sustainable balance between the Sudd's ecological health and the local communities' prosperity.

7.2.2 Methodological contribution: integrating empirical data and flood hazard and exposure mapping

Chapter 4, a geospatial analysis of population exposure to flooding in the Sudd region, provides an example of how global datasets can underpin policy and decision-making in data scarce areas such as South Sudan. Recognizing the inevitable limitations of the application of global datasets in the Sudd context, this thesis intersects all the available global flood modelling products and population datasets to characterize population exposure in the Sudd region. The study demonstrates the global significance of model intercomparison as best practice for any flood exposure analysis to underpin policy and decision-making in Africa and other data-scarce regions.

Realizing that the fast-changing dynamics of extreme flooding in the Sudd region are complex and cannot be fully learned in flood model simulations, devoid of lived experiences, a dynamics of human adaptation to flood risk in the Sudd wetland study (Chapter 5) was conducted, as understanding the full consequences of a human-flood interaction requires experiencing it first-hand. This study overcame a seven-decade long (1955-2025) difficulty in conducting in-situ

research in the Sudd region because of inaccessibility due to poor infrastructure and prolonged conflict. The empirical component of the thesis uses a thematic analysis of field data acquired through multi-method approaches, including focus group discussions and semi-structured interviews, participatory mapping, field observation documentations, and multi-stakeholder engagement. The field study involved respondents in their natural environments and contexts, knowing this approach encourages respondents to speak more freely and creates the opportunity for community qualitative mobility exercises. The thesis therefore unearths long absent human eyes, ears, and voice in the Sudd region, and brings to the forefront rich human-flood learnings, juxtaposing empirical findings with results from flood hazard and population exposure modelling.

Beyond the comprehensive population exposure modelling and the in-depth field study, the thesis produces field-based migration rules and exposure scenarios under climate change (Chapter 6) to estimate and characterize migration flows among some of the most vulnerable communities in Sudd region. This is the first insight into the long trend of migration flows produced from the combination of decision rules derived from a field study in the Sudd region and population exposures scenarios.

7.2.3 Contextual contribution

This thesis is undertaken in one of the most difficult and inaccessible regions in the world. Given limited in-situ-data, there is high demand for the georeferenced population datasets particularly in countries with less detailed or infrequent censuses (Lyek et al., 2019) such as South Sudan. The first phase of the thesis uses gridded global datasets in lieu of census data

and offers the first comprehensive flood mapping and exposure for the Sudd region by mapping South Sudanese spatial population distribution and population density. The study uses results from model intercomparison, historical gauge flows into the Sudd, and relevant literature to identify sites for the field study in Phase Two of the thesis. Given this understanding, the thesis focuses its second phase by diving deep into inter-generational flood-human interaction in the Sudd region. Through a field study conducted between February and June 2024, amidst recurrent conflicts, in high flood water, and through the Sudd's reach, the thesis makes a breakthrough to produce the first comprehensive and in-depth study whose results are representative of the landscape and communities in the Sudd region. This thesis brings to the fore a comprehensive flood and societal interaction for the first time in the Sudd region and has the potential to inform communities' resilience plans and flood risk management planning at various scales in the Sudd region. In the Sudd region setting, where natural disasters surprise humans due to a lack of an early warning and monitoring system, this thesis produces a long-range synthesis from future climate scenarios and population exposure projections to estimate migration flows among some of the most vulnerable communities to climate change in the Sudd region.

7.2.4 Summary of contribution

First, the thesis develops a systematic geospatial assessment of population exposure to flooding. In contrast to earlier approximations, this approach enables a more precise identification of populations at risk under both current and projected flood conditions. The analysis indicates that counties assessed in Jonglei, Unity, and Upper Nile states experience the highest levels of

exposure, thereby providing a more rigorous empirical basis for understanding spatial patterns of vulnerability.

Second, the thesis offers new empirical insights into the socio-environmental consequences of prolonged and extreme flooding. From the field visits and observation, the study documents a marked shift from nomadic and semi-nomadic transhumance towards more permanent forms of settlement uplands in upstream regions, suggesting that recurrent flooding is contributing to the reconfiguration of pastoralist livelihoods. In addition, the research investigates the cultural significance of territories that have become permanently inundated, extending beyond economic interpretations of land loss to consider implications for identity, memory, and social organization among communities such as the Dinka, Nuer, and Shilluk.mThe thesis also bridges indigenous knowledge and scientific hydrological perspectives. In doing so, it departs from approaches that privilege large-scale technical interventions as principal solutions and instead adopts a socio-hydrological framework that situates contemporary flooding within longer-term patterns of environmental understanding and adaptation. This perspective is particularly relevant considering the extreme flooding observed since 2019, which has altered established relationships between hydrological processes and local populations.

Third, the thesis advances a conceptual framework linking flooding, migration, and inter-communal relations. Applying this framework, the thesis identifies the potential for tension between displaced and host communities, highlighting the social and cultural risks associated with relocation processes. This framework contributes to a more integrated understanding of how environmental change may interact with existing social and political dynamics. Finally, the research offers context-sensitive policy considerations. Rather than focusing solely on large-scale infrastructural debates, such as dredging or the Jonglei Canal, it emphasizes the

importance of approaches that integrate local knowledge, hydrological analysis, and broader resilience strategies. These considerations are intended to inform more contextually grounded responses to flooding in the Sudd region.

7.3 Policy recommendations: integrated policy pathways for flood resilience in the Sudd wetland system

This section synthesizes ten strategic policy recommendations into a coherent analytical framework, situating them within broader debates on climate adaptation in fragile, hydrologically dynamic environments. To enhance clarity and analytical coherence, policy recommendations are presented in a two-tier format: a summary matrix (Table 17A) and detailed implementation pathways (Table 17B).

Table 17: Summary matrix (Table 17A) and detailed implementation pathways (Table 17B).

Table 17A: Summary policy matrix: integrated pathways for flood resilience in the Sudd wetland.

#	Policy Recommendation	Core Problem	Key Intervention	Lead Actors	Timeframe	Intended Impact
1	Community-Based Early Warning Systems (CBEWS)	Lack of timely,	Village-level SMS/radio alert networks	Ministry of Environment	Short-term (1–3 yrs)	Reduced mortality and asset loss

#	Policy Recommendation	Core Problem	Key Intervention	Lead Actors	Timeframe	Intended Impact
		localized flood warnings		; Telecom providers		
2	Flood-Resilient Infrastructure (Flood Hubs)	Service inaccessibility during floods	Elevated, solar-powered service hubs	Government; World Bank; GCF	Medium-term (3–10 yrs)	Continuity of health and education services
3	Cross-Border Water Governance	Lack of upstream hydrological data	Nile Basin data-sharing protocols	Nile Basin Initiative; AU; IGAD	Medium-term	Improved flood forecasting and preparedness
4	Climate-Adaptive Land Tenure Reform	Farmer–pastoralist conflict over land	Seasonal "climate-buffer zones"	National Land Commission; Traditional leaders	Medium-term	Reduced conflict; adaptive land use
5	Socio-Hydrological Education	Loss of indigenous knowledge	"Living with Water" curriculum	Ministry of Education	Long-term (10+ yrs)	Intergenerational resilience and adaptation
6	Mobile Service Delivery	Disrupted services during displacement	Floating clinics and mobile schools	Government; UNICEF; WFP	Short–Medium	Sustained service delivery during floods

#	Policy Recommendation	Core Problem	Key Intervention	Lead Actors	Timeframe	Intended Impact
7	Green Infrastructure & Wetland Restoration	Wetland degradation; overreliance on hard infrastructure	Papyrus restoration; nature-based buffers	Ministry of Environment	Long-term	Ecological resilience; flood attenuation
8	Livelihood Diversification	Declining pastoral livelihoods	Aquaculture and flood-recession farming	FAO; UNDP	Short–Medium	Increased income resilience
9	Flood-Relief Accountability	Aid diversion and weak governance	Community-led monitoring systems	CSOs; Donors	Short-term	Improved transparency and trust
10	National Flood-Migration Framework	Conflict-driven, unplanned migration	Planned relocation and migration corridors	Multi-ministry coordination; IOM	Medium–Long	Reduced conflict; orderly migration

Table 17B: Detailed policy pathways for flood resilience in the Sudd wetland.

Column A (Policies 1–5)

1. **Community-Based Early Warning Systems (CBEWS)**

Problem: Lack of timely, localized flood warnings; "last-mile failure."

Evidence & Scale: Fast-onset flood peaks overwhelm coping systems (Basher, 2006).

Recommendation: Village-level monitoring using SMS/radio alerts.

Alternatives rejected: Satellite-only systems; large dams.

Implementation: Ministry of Environment + telecoms; trained local volunteers.

R**esources**: Mobile networks; low-cost training.

Risks: Alert fatigue; false alarms.

Best Practice: Bangladesh CPP.

2. **Flood-Resilient Infrastructure (Flood Hubs)**

Problem: Services inaccessible during floods.

Evidence & Scale: Populations cut off for

Column B (Policies 6–10)

6. **Mobile Service Delivery (Floating Clinics & Schools)**

Problem: Displacement disrupts access to services.

Evidence & Scale: Flood displacement lasts months (Kratli, 2001).

Recommendation: Boat-based clinics and mobile schools.

Alternatives ejected: Fixed camps; waiting for flood recession.

I**mplementation**: Cross-ministerial coordination; route-based deployment.

Resources: UNICEF/WFP funding; boats; staff.

Risks: High operational cost; security concerns.

Best Practice: Kenya mobile schools.

7. **Green Infrastructure & Wetland Restoration**

Problem: Wetland degradation; overreliance on hard infrastructure.

Column A (Policies 1–5)	Column B (Policies 6–10)
months (World Bank, 2024). **Recommendation**: Elevated, solar-powered service hubs. **Alternatives rejected**: Large-scale Nile engineering. **Implementation**: Integrated into infrastructure planning. **Resources**: World Bank; GCF; engineers. **Risks**: Elite capture; inequity. **Best Practice:** Vietnam "Living with Floods."	**Evidence & Scale**: Natural buffers reduce flood risk (Mitsch & Gosselink, 2015). **Recommendation**: Papyrus restoration; nature-based buffers. **Alternatives rejected:** Hard engineering-only. **Implementation**: Ministry of Environment; NDC integration. **Resources**: Carbon credits; conservation funding. **Risks**: Reduced farmland; resistance. **Best Practice:** China "Sponge Cities."
3. **Cross-Border Water Governance Protocols** **Problem**: Lack of upstream data; reactive management. **Evidence & Scale**: Floods linked to upstream rainfall (2019–2022 events). **Recommendation**: Nile Basin data-sharing (7–14 day lead time). **Alternatives rejected**: Unilateral dams; non-cooperation.	8. **Livelihood Diversification (Aquaculture & Flood Farming)** **Problem**: Declining pastoral livelihoods. **Evidence & Scale**: Reduced livestock productivity (Ellis, 2000). **Recommendation:** Aquaculture and flood-recession crops. **Alternatives rejected**: Forced farming; large irrigation. **Implementation**: FAO Farmer Field

Column A (Policies 1–5)

Implementation: Hydrologist secondments; formal agreements.

Resources: IGAD; AU support.

Risks: Political tensions; sovereignty concerns.

Best Practice: Senegal River Basin (OMVS).

4. **Climate-Adaptive Land Tenure Reform**

Problem: Farmer–pastoralist conflict.

Evidence & Scale: Linked to inter-ethnic violence (Cotula, 2007).

Recommendation: Seasonal "climate-buffer zones."

Alternatives rejected: Forced settlement; laissez-faire.

Implementation: Land Commission + traditional leaders.

Resources: Legal reform; mediators.

Risks: Political resistance; land disputes.

Best Practice: Niger Rural Code.

Column B (Policies 6–10)

Schools.

Resources: UNDP; extension services.

Risks: Cultural resistance.

Best Practice: Cambodia Tonle Sap.

9. **Transparent Flood-Relief Accountability**

Problem: Aid diversion; weak governance.

Evidence & Scale: Leakage common in fragile states (Adger et al., 2003).

Recommendation: Community-led monitoring systems.

Alternatives rejected: Centralized audits only.

Implementation: Support CSOs; reporting tools.

Resources: Donor funding.

Risks: Retaliation against monitors.

Best Practice: Philippines "Open Reconstruction."

Column A (Policies 1–5)	Column B (Policies 6–10)
5. **Socio-Hydrological Education** **Problem**: Loss of traditional knowledge. **Evidence & Scale**: Generational knowledge gap (Sivapalan et al., 2012). **Recommendation**: "Living with Water" curriculum. **Alternatives rejected:** NGO-only education. **Implementation**: Ministry of Education; teacher training. **Resources**: Curriculum development. **Risks**: Limited reach if attendance low. **Best Practice**: Netherlands "Room for the River."	10. **National Flood-Migration Framework** **Problem**: Unplanned migration causing conflict. **Evidence & Scale**: Migration linked to violence (Ferris, 2015). **Recommendation**: Planned relocation; safe corridors. **Alternatives rejected**: Forced returns; inaction. **Implementation**: Multi-ministry coordination. **Resources**: IOM; AU support. **Risks**: Permanent displacement ("brain drain"). **Best Practice**: Fiji relocation guidelines.

The findings underscore that flood risk in the Sudd is not solely a biophysical phenomenon, but a deeply socio-hydrological challenge, requiring interventions that simultaneously address governance, mobility, knowledge systems, and ecological processes, as demonstrated through the policy recommendations that follow.

7.3.1 From forecasting to “last-mile” adaptation: community-based early warning systems (CBEWS)

The analysis demonstrates that the primary failure of existing early warning systems lies not in predictive capacity, but in distributional inefficiency at the community level. Flood events in the Sudd are increasingly characterized by rapid onset, leaving minimal time for response and overwhelming traditional ecological knowledge systems. This aligns with broader evidence that “last mile” communication is often the weakest link in disaster risk reduction, where even accurate forecasts fail to translate into actionable knowledge (Basher, 2006). The are great challenges in turning high-level adaptation plans into real, on-the-ground actions that reach those who need them most. The proposed Community-Based Early Warning Systems (CBEWS), grounded in radio and SMS communication, reflect a shift toward human-centered sensing networks. Empirical and programmatic evidence suggests that localized monitoring and dissemination mechanisms improve both trust and responsiveness, particularly in fragile contexts where state capacity is limited (Andreadis et al., 2022; UNDP, 2025; Skuse et al., 2013). The success of volunteer-based models in comparable settings further reinforces the importance of social infrastructure over technological sophistication.

While this recommendation is not primarily grounded in a detailed technical assessment of forecasting systems within this study, it is strongly supported by the empirical evidence on human exposure and vulnerability generated in the Sudd region. The findings demonstrate that the absence—or severe breakdown—of early warning dissemination mechanisms significantly exacerbates flood impacts. Communities repeatedly reported being caught off guard by rising floodwaters, despite the broader predictability of seasonal flooding patterns. This disconnect

highlights a critical gap between hazard awareness at macro scales and actionable preparedness at the household level.

Evidence from recent flood events in South Sudan, particularly since the prolonged flooding crises beginning in 2019, shows that early warning information—where it exists—is often delayed, spatially uneven, or inaccessible to remote wetland communities. Humanitarian assessments (e.g., OCHA, FAO, and WFP reports) consistently document that many flood-affected populations in the Sudd received little to no advance warning prior to displacement. In several counties across Jonglei and Unity States, households reported relying on reactive coping strategies—such as emergency migration with livestock—rather than anticipatory action, due to lack of timely information. This has contributed directly to loss of lives, livestock mortality, food insecurity, and the erosion of livelihood systems. Furthermore, the institutional fragmentation and limited communication infrastructure in the Sudd region compound this problem. Early warning information generated at national or regional levels is rarely translated into locally relevant, trusted, and understandable formats. In many cases, warnings do not reach pastoralist and agro-pastoralist communities who are highly mobile and geographically isolated. This reinforces the argument that the effectiveness of forecasting is not determined solely by predictive accuracy, but by the extent to which information is embedded within local social systems and decision-making processes.

Therefore, the shift from forecasting to “last-mile” adaptation is not merely a technical adjustment, but a structural reorientation of flood risk management. Community-Based Early Warning Systems (CBEWS) offer a practical pathway to bridge this gap by decentralizing both data collection and communication. By integrating local observers, community leaders, and existing communication channels (such as FM radio, mobile phones, and social networks),

CBEWS can transform early warning from a top-down product into a participatory process. This enhances not only the timeliness of warnings but also their legitimacy and uptake.

7.3.2 Decentralizing critical infrastructure: toward flood-resilient service provision

Extreme flooding in South Sudan generates prolonged disruptions in service delivery, producing what can be conceptualized as "hydrological service deserts," where entire populations are cut off from healthcare, education, markets, and humanitarian assistance for extended periods (Borgomeo et al., 2023). These disruptions are not only environmental but systemic, reflecting the high spatial concentration and fragility of existing infrastructure, which is often located in flood-prone areas and dependent on limited road networks. While decentralized "flood hubs"—elevated, distributed, and climate-resilient service nodes—represent a promising adaptation strategy, their effectiveness in the Sudd is contingent on institutional, political, and logistical realities. Decentralization does not automatically translate into resilience; in fragile contexts, it can instead lead to fragmented service provision, uneven quality, and increased exposure to local elite capture or conflict dynamics.

Moreover, the assumption that infrastructure can be "climate-proofed" must be treated cautiously. The Sudd's hydrology is highly dynamic and increasingly unpredictable, meaning that infrastructure designed for historical flood patterns may quickly become obsolete. As such, resilience should be understood not as permanence, but as flexibility, redundancy, and capacity for rapid adaptation. Decentralized flood-resilient infrastructure should be pursued as part of a networked and adaptive service delivery model, rather than a purely spatial redistribution of

assets. This requires integrating physical infrastructure with governance arrangements, mobility systems, and contingency planning. Key strategic directions include:

Developing modular and mobile service platforms (e.g., floating clinics, temporary learning centers, amphibious logistics units) that can adjust to shifting flood conditions rather than relying solely on fixed infrastructure.

Establishing tiered service networks, where decentralized hubs are linked to regional centers through flexible supply chains (including river transport and air support during peak flooding).

Prioritizing multi-functional infrastructure (e.g., elevated platforms serving as clinics, schools, and emergency shelters) to maximize utility under resource constraints.

Embedding community-based management structures, while ensuring external oversight to mitigate risks of elite capture and exclusion.

7.3.3 Transboundary hydrology and cooperative governance

The Sudd's hydrological dynamics are intrinsically linked to upstream processes within the Nile Basin, rendering national-level interventions insufficient in isolation. The findings highlight that extreme flood events are partly driven by upstream rainfall variability and water releases, necessitating coordinated basin-wide management (Grigg, 2024). Existing frameworks such as the Nile Basin Initiative provide a foundation for data-sharing and cooperative governance, yet

remain underutilized at the national level. The literature suggests that cooperative approaches to water management yield greater collective benefits than unilateral control, particularly when framed around shared gains rather than zero-sum allocation (Sadoff and Grey, 2002). However, the political sensitivities surrounding "historical water rights" underscore the need for careful diplomatic engagement.

7.3.4 Land, mobility, and conflict: the case for flexible tenure systems

One of the most significant findings of this study is the centrality of land-use conflict as a mediating variable between climate shocks and violence. Flood-induced migration disrupts established patterns of land use, bringing pastoralists and agricultural communities into competition over diminishing dry land. Empirical evidence identifies such conflicts as a key driver of inter-communal violence in South Sudan (Deng et al., 2024; International Crisis Group, 2026). Importantly, these conflicts are rarely resource-based alone; they are deeply entangled with ethnic identities, historical territorial claims, and legacies of civil war, which amplify competition and reduce the scope for cooperative resource sharing.

Current land tenure systems, which privilege static ownership, are poorly suited to dynamic floodplain environments. The proposed introduction of "climate-buffer zones" reflects a broader theoretical argument that flexible, negotiated land rights are more effective in fragile contexts than rigid legal frameworks (Cotula, 2007). This approach aligns with customary

governance systems among the local communities and acknowledges mobility as an adaptive strategy rather than a problem to be constrained.

However, the assumption that flexibility reduces conflict must be treated with caution. In highly fragmented and ethnically polarized settings, flexible tenure arrangements may lack enforceability and can be interpreted as ambiguity over ownership, thereby exacerbating disputes rather than resolving them. Customary systems themselves are not neutral; they may privilege dominant groups, exclude minorities, or be manipulated by local elites, particularly where authority is contested or militarized.

Furthermore, increasing climate-induced mobility risks transforming seasonal access arrangements into more permanent or semi-permanent settlement patterns, intensifying perceptions of encroachment and triggering defensive territorial claims. In such contexts, “climate-buffer zones” may become sites of contestation if boundaries, access rights, and governance mechanisms are not clearly defined and collectively legitimized.

Operationalizing flexible tenure therefore requires careful sequencing and conflict-sensitive design. This includes establishing locally legitimate negotiation platforms, clarifying overlapping rights (e.g., grazing, cultivation, fishing), and linking customary arrangements with higher-level legal and administrative support where possible. Without credible dispute resolution mechanisms and enforcement capacity, flexible systems risk remaining informal agreements that break down under stress.

Additional constraints include limited state capacity to formalize or support negotiated arrangements, the proliferation of armed actors influencing land access, and the risk that

external interventions unintentionally legitimize contested authorities. At the same time, there are opportunities to leverage shared dependence on floodplain resources to foster negotiated coexistence, particularly where interdependence between livelihood groups remains strong.

7.3.5 Knowledge systems and the socio-hydrological interface

The erosion of traditional ecological knowledge, coupled with limited formal climate education, has created a knowledge deficit among younger generations, threatening discontinuity of traditional clues, norms and customs. Over 200 participants across 15 social groups expressed unanimous observation sudden disruption of their social cohesion considering flood-induced migration during 2019-2024 extreme flooding. This gap undermines adaptive capacity and weakens the feedback loop between human behavior and hydrological processes. Emerging scholarship in socio-hydrology emphasizes the importance of integrating scientific and local knowledge systems to enhance resilience (Zhang et al., 2016; Orieschnig et al., 2025). Embedding flood adaptation within national curricula represents a long-term investment in behavioral transformation, fostering a population capable of coexisting with, rather than resisting, hydrological variability.

7.3.6 Mobility as adaptation: rethinking service delivery

Flood-induced displacement in the Sudd is neither temporary nor exceptional; it is a structural feature of the Sudd-system. Evidence indicates that displacement often persists for extended

periods, disrupting access to essential services and exacerbating vulnerability (Researching Internal Displacement, 2024). The concept of mobile service delivery challenges conventional models of fixed infrastructure, proposing instead that services should follow migrating populations along established mobility corridors. This approach is particularly relevant for pastoralist communities, in settings such as the Sudd, for whom mobility is a core livelihood strategy. The literature supports this perspective, suggesting that static service provision can inadvertently reinforce exclusion (Kratli, 2001).

However, operationalizing mobile service delivery in the Sudd context faces significant constraints that must be explicitly addressed. First, insecurity and localized conflict—often linked to cattle raiding, inter-communal tensions, and militarized access to territory—can severely restrict the safe movement of service providers and undermine continuity of delivery. Second, the extreme seasonal variability and hydrological unpredictability of the Sudd limit physical access, as large areas become inaccessible for months due to flooding, poor transport infrastructure, and lack of navigable routes. Third, institutional fragmentation and limited state presence reduce coordination capacity, raising risks of duplication, gaps in coverage, and uneven service quality across mobile populations. Fourth, financing models for mobile systems remain underdeveloped, as most humanitarian and development funding mechanisms are structured around fixed, place-based service delivery and short-term project cycles rather than sustained, adaptive mobility.

Additionally, mobile service provision must contend with socio-political sensitivities around territory, identity, and belonging. Movement across administrative or customary boundaries may trigger tensions with host communities, particularly where land and water resources are

already contested. Without careful negotiation and community engagement, mobile services risk being perceived as favoring certain groups, thereby exacerbating inequalities or conflict dynamics. Finally, the absence of reliable population data and tracking systems for mobile groups complicates planning, targeting, and accountability, potentially leading to exclusion errors or inefficient allocation of resources.

These constraints suggest that while mobility-oriented service delivery is conceptually compelling, its implementation requires robust conflict-sensitive planning, flexible financing instruments, investment in amphibious and context-appropriate logistics, and strengthened coordination between humanitarian, governmental, and local governance systems.

7.3.7 Nature-based solutions and the limits of hard infrastructure

The findings reinforce the limitations of hard-engineering approaches in the Sudd, where attempts to control water through dikes, dredging or canals often generate unintended ecological and social consequences. In contrast, wetlands function as natural flood buffers, absorbing excess water and reducing downstream impacts. Research on nature-based solutions demonstrates their effectiveness in enhancing flood resilience while maintaining ecosystem services (Enu et al., 2023). Wetlands provide critical benefits as carbon sinks and biodiversity hotspots, reinforcing their role in both climate mitigation and adaptation (Mitsch & Gosselink, 2015). This supports a paradigm shift toward working with, rather than against, natural systems—an approach that reflects the co-evolution of human–water systems and aligns with the aspirations of local communities to live with water, given their dependence on its resources.

7.3.8 Livelihood transformation and adaptive capacity

The observed decline of pastoralism in the Sudd region reflects not only ecological change driven by prolonged flooding, but also compound pressures from insecurity, restricted mobility, and market fragmentation. While flooding reduces grazing availability and contributes to declining herd sizes, the erosion of pastoral systems is equally shaped by disrupted transhumance routes, cattle raiding, and the breakdown of traditional resource governance. As such, pastoralism is not simply becoming less viable—it is being structurally constrained. Empirical evidence indicating declining herd sizes and increased reliance on low-return coping strategies (WeAdapt, 2023; ReliefWeb/SPARC, 2023) suggests that many households are not actively "transforming" livelihoods, but rather being pushed into distress-driven diversification. This distinction is critical: diversification under duress often leads to precarious, low-productivity activities that do little to enhance long-term resilience.

While diversification into aquaculture and flood-recession agriculture aligns with broader evidence that multi-income strategies can buffer environmental risk (Ellis, 2000), the feasibility of such transitions in the Sudd is highly uneven. These livelihood pathways require access to inputs, technical knowledge, stable water regimes, and functioning markets—conditions that are often absent in remote and conflict-affected areas. Without these enabling factors, diversification risks reproducing vulnerability rather than alleviating it.

Moreover, pastoralism in South Sudan is not merely an economic system but a core socio-cultural institution, underpinning identity, social relations, and systems of wealth and bride price. Abrupt or externally driven transitions away from cattle-based livelihoods risk

undermining social cohesion and may generate resistance or unintended conflict dynamics. Livelihood transformation should, therefore, not be framed as a linear shift away from pastoralism, but as a hybrid adaptation process that strengthens, adapts, and selectively diversifies existing systems. This requires a context-sensitive and phased approach that expands adaptive capacity while preserving socio-cultural foundations.

7.3.9 Governance, trust, and accountability in fragile contexts

central constraint emerging from the country-level analysis in South Sudan is not simply weak governance, but the coexistence of formal institutional fragility and strong informal power structures. The diversion and capture of aid resources by political and local elites is not an anomaly but a structural feature of hybrid governance systems, where authority is negotiated across state actors, customary leaders, and armed groups. As a result, externally driven accountability frameworks often fail because they are misaligned with the actual loci of power.

While evidence suggests that community-led accountability mechanisms can enhance transparency and rebuild trust (Transparency International, 2023), their effectiveness is highly contingent on local power relations, social cohesion, and protection from elite interference. In fragmented or conflict-affected communities, such mechanisms risk being co-opted, reinforcing exclusion rather than promoting accountability. Similarly, the role of social capital in strengthening disaster resilience (Adger, 2003) must be interpreted cautiously; bonding social capital may enhance intra-group resilience while simultaneously marginalizing outsiders or minority groups. Rather than assuming that accountability can be “embedded” within existing

structures, interventions should adopt a politically informed and adaptive approach that explicitly recognizes governance constraints. This includes:

Supporting hybrid accountability systems that combine community monitoring with independent third-party verification (e.g., NGOs, faith-based networks, or international partners).

Investing in transparency infrastructure (e.g., open beneficiary registries, digital cash transfers, satellite-based monitoring of aid delivery) that reduces opportunities for elite capture.

Strengthening downward accountability incentives, such as conditional funding tied to verifiable community feedback rather than top-down reporting.

Sequencing reforms realistically, prioritizing "good enough governance" over idealized institutional models.

In summary, accountability in the Sudd region should not be treated as a technical add-on to governance, but as a deep political process shaped by power, incentives, and context. Effective policy must therefore move beyond institutional templates and engage directly with the realities of fragility, adopting flexible, context-sensitive strategies that balance ambition with feasibility.

7.3.10 Planned relocation and the governance of climate mobility: flood migration framework.

The study highlights the absence of a coherent framework for managing flood-induced migration. Current patterns of movement are largely unregulated, contributing to resource competition and violent conflict (PeaceRep, 2024; Chol et al., 2026). The development of a national flood-migration framework, including planned relocation and designated mobility corridors, represents a proactive approach to managing climate mobility. The literature emphasizes that relocation must be anticipatory, participatory, and rights-based to avoid exacerbating vulnerability (Ferris, 2015). Importantly, such frameworks should preserve the option of return, maintaining connections to ancestral land.

In summary, these findings point toward the need for a fundamental reorientation of flood governance in the Sudd. Rather than pursuing control-based strategies, the evidence supports an adaptive model characterized by decentralization of infrastructure and governance, flexibility in land tenure and service delivery, localization of knowledge and early warning systems, integration of ecological processes into policy design, and regional cooperation in transboundary water management. This integrated approach reflects the core insight of socio-hydrology: that human and water systems are co-evolving, and that resilience emerges not from resisting change, but from adapting to it.

7.3.11 Summary of the policy recommendations

Beyond the academic research, findings from this research have been stress-tested through direct engagements with the various key stallholders, including the traditional leaders and state governments in the flood affected areas, national Government of South Sudan, with presentations of the findings delivered to the cabinet, parliament, and the public. Consequently, the study translates global modelling insights, learnings from five months of comprehensive empirical fieldwork, and synthesis from multi-stallholders engagement into these ten credible, actionable policy recommendations. These proposals are grounded in local reality yet informed by global best practices.. The recommendations are developed in two distinct phases. First, the thesis identifies ten high-priority interventions tailored to the specific needs of the Sudd. Second, the study provides a rigorous breakdown for each of the recommendations—evaluating the evidence base, projected scale of impact, rejected alternatives, implementation pathways, resource requirements, and potential unintended consequences.

Lastly, to strengthen the credibility of these recommendations, global precedents where similar strategies have succeeded in fragile or flood-prone contexts are provided (Table 17A/17B). To ensure these recommendations are "credible" for a fragile state such as South Sudan and some of its neighbors, they prioritize low-cost/high-impact wins, community-led resilience, and transboundary cooperation, developing the Sudd as " common" resources: the lungs of the Nile Basin.

7.4 Implications of the policy recommendations for decision-making

Below is a concise, multi-level synthesis of the implications of the ten policy recommendations, which are based on the key findings from this study, across four governance scales: (7.4.1) Nile Basin region, (7.4.2) South Sudan, (7.4.3) Sudd region, and (7.4.4) community level. As described below, each level highlights how the recommendations translate into practical shifts in governance, infrastructure, and behavior.

7.4.1 Implications at the Nile Basin regional level

At the Nile Basin scale, the ten recommendations imply a shift toward coordinated, adaptive transboundary governance that treats flood dynamics as a shared system rather than a national externality. This requires strengthening the Nile Basin Initiative into an operational platform for real-time data sharing, joint flood forecasting, and basin-wide early warning dissemination, alongside embedding wetlands like the Sudd as critical natural infrastructure within regional planning. The increasing trends in cross-border migration transcend dynamics within South Sudan, and necessitates the creation of a common migration policy by East African governments that guide a bilateral and multilateral collaboration between South Sudan, Kenya, DRC, and Uganda. Cross-border migration leads to complex challenges including potential conflict between countries. These challenges exist beyond the capacity of an individual country. The policy recommended entails formal recognition of cross-border mobility (especially

pastoral corridors), harmonization of climate knowledge systems, and development of shared principles for climate-induced displacement, thereby reframing cooperation around mutual resilience gains rather than water allocation conflicts.

A comprehensive approach to water resources development and flood risk management in the Nile Basin requires a better understanding of regional water resources management, including dam operations in the immediate upstream countries of Uganda and Kenya. Regional or national intervention approaches in flood or water resources management must account for the effects of such measures on the socio-economic dimension of the communities downstream. To avert total instability in border areas that are currently characterized by fragility, all the Eastern African countries must leverage their collective strategic resources, security intelligence, and human resources. This long range outlook of dynamics of transboundary migration, from this study, should guide a new East Africa regional policy, including governance frameworks on transhumance and population migration along the borders.

7.4.2 National-scale implications

This thesis contributes to the Government of South Sudan's calls (2018, 2022, 2024) for a better understanding of future flood risk and resulting impacts on communities and populations, and highlights the importance of incorporating hydrologic change into future flood risk management plans for the Sudd region. At present, the national government (through the Ministry of Environment and Forestry and Ministry of Water Resources and Irrigation) is studying a project to implement "No-regret water management and livelihood interventions in flood-affected and refugee hosting areas of South Sudan, funded by the World Bank. This

project involves international non-governmental organizations (NGOs) and private companies that have engaged in the construction of small-scale water infrastructures. However, the effects of such short-term fixes on the long-term resilience of pastoralists and the larger communities are limited and mostly ignored by the stakeholders implementing water infrastructure interventions. It is important to assess how these conceptual projects will influence the Sudd communities' interactions with flooding, and to incorporate the key findings and Indigenous knowledge captured in the design and implementation of such projects. This is also true for the ongoing Egyptian dredging project in Bahr el Naam (in the Bahr el Ghazal River Basin), which was approved in 2022 by the Government of South Sudan "to allow the free flow of water to mitigate floods." It is unclear how such looming large-scale projects will influence the dynamics in the Sudd socio-hydrological system in the Sudd region, which creates fundamental uncertainties that warrant further study.

This study data documents that the impact of the 2019-2024 historic flooding were amplified by a lack of early warning systems, resulting in greater loss of life, property damage, and livelihood disruption. At the national level, the ten policy recommendations collectively imply a fundamental reconfiguration of state roles in climate adaptation, shifting from centralized, control-oriented governance toward a decentralized, adaptive, and facilitative model. This entails prioritizing investment in last-mile communication systems – in local languages- to translate forecasting capacity into actionable early warning, alongside the development of distributed, flood-resilient service infrastructure that ensures continuity of healthcare, education, and markets during hydrological shocks (extreme flooding events). Furthermore, for the local population to access weather information or forecast data, a communication system,

using diverse local languages, needs to be linked to local social institutions and networks such as cattle camps, fishing camps, village chiefs, religious organizations, and local courts.

To prevent economic losses due to the impacts of migration dynamics on its critical transport roads/routes that facilitate the export and imports flows with Uganda, Kenya, and Ethiopia, the government of South Sudan must invest in sustainable transformative approaches that can reduce flood risk and migration flows. Institutional reform at the national level and across state-lines is required to embed flexibility within land tenure systems, formally recognizing mobility as an adaptive strategy and aligning statutory frameworks with customary practices to mitigate conflict. Concurrently, the state must integrate interdisciplinary knowledge systems—particularly insights from Socio-hydrology—into national education and policy processes, thereby strengthening long-term adaptive capacity. Service delivery models must also be reimagined to accommodate mobile populations, while livelihood policies should support diversification into flood-compatible economic activities. Critically, these shifts depend on improved governance, including enhanced transparency, community-led accountability mechanisms, and strengthened institutional legitimacy in fragile contexts.

At the same time, South Sudan's engagement in transboundary water governance through frameworks such as the Nile Basin Initiative must be deepened to incorporate basin-wide hydrological dynamics into national planning. Finally, the establishment of a coherent, rights-based framework for planned relocation and climate mobility is essential to proactively manage displacement, reduce conflict, and preserve socio-economic stability. Taken together, these implications position the state not as a controller of floods, but as an enabler of systemic adaptation within a dynamic socio-hydrological landscape. The Government of South Sudan

should prioritize urgent interventions in States of Unity, Jonglei, Upper Nile, and Warrap as these are areas with exceeding flood hazards and the highest population exposures.

At the national level, it is necessary for South Sudan to focus more attention on modifying its water policy. A modified policy must include guidelines that make visible the complex and intertwined impacts of extreme flooding, including migration, conflict, and community settlement as contributing to threats to national stability. Reframing the national water policy to encompass these merging flood related existential threats can refocus the government to invest intensively in the wellbeing and stability of the local communities in the Sudd region.

As a result of South Sudan increasing migration trend across state lines the IDPs, without plans, have been brought together by floods to common spaces. However, the proximity of the IDP camps in Unity State, Upper Nile, Central Equatoria, Jonglei State, and Warrap to the UN and government premises, considering population perceptions of protection or provision, creates an opportunity for efficient service delivery and a new unity among ethnically diverse populations. To advance this new unity, the state authorities can play a convening role and establish platforms for the local authorities, traditional chiefs, and IDPs representatives. States should support community-led initiatives by the migrants and the host communities across different ethnic groups toward a shared destiny. The national and states' investment should include a forward looking plan that can effectively address the growing conflict between the host communities and the IDPs. That plan should provide an enabling environment for a grassroot-level inter-communal dialogue and a regulatory framework for managing jurisdictional issues and disputes over land among IDPs, pastoralists, and local farmers. Then, the community chiefs and the local authorities should devise a new policy of common resettlement and reintegration. Community-led efforts to foster peaceful coexistence initiatives directed at reintegration - both

traditional and modern - among the young people across different clans, ethnic groups, or geographies promise a new dawn for the unity among South Sudanese.

7.4.3 Sudd regional-level implications (aligned with Tables 17A–17B)

This study bridges the gap between reactive disaster response and proactive flood risk management by demonstrating how spatial patterns of exposure can inform targeted, context-sensitive interventions. The findings directly underpin the strategic pillars outlined in Table 17A and their corresponding operational pathways in Table 17B, providing an integrated framework for advancing resilience in the Sudd region.

At the regional scale, the results emphasize the need to operationalize hydrologically aligned, location-specific adaptation systems (Table 17A: *Flood forecasting and early warning systems*; Table 17B: *localized early warning networks and forecast translation mechanisms*). Translating basin-scale hydrological forecasts into actionable, community-level responses is critical to reducing loss of life and livelihoods.

The study further highlights the importance of risk-informed spatial planning and infrastructure development (Table 17A: *Flood-resilient infrastructure and urban planning*; Table 17B: *elevated service hubs, flood-compatible infrastructure, and zoning reforms*). Empirical evidence shows that unplanned urbanization—particularly the obstruction of natural drainage channels by settlements, roads, and bridges—has significantly amplified flood impacts. Towns such as Bentiu, Rubkona, Leer, Mayendit, Bor, Twic East, Old Fangak, Tonga, Nasir, Maiwut,

Akop, Kuajok, and Wunrok exemplify the urgent need for spatial planning systems that explicitly integrate flood risk into land-use decisions.

In parallel, the findings reinforce the role of nature-based solutions and ecosystem protection (Table 17A: *Ecosystem-based flood management*; Table 17B: *wetland conservation, restoration, and flood buffering strategies*). Protecting the ecological integrity of the Sudd wetlands is not only an environmental priority but also a critical component of flood regulation and long-term resilience.

The research also underscores the necessity of livelihood diversification and food system resilience (Table 17A: *Livelihood adaptation and food security*; Table 17B: *hybrid livelihood systems and climate-resilient agriculture*). Addressing food insecurity—particularly among internally displaced populations—requires coordinated investments in agricultural productivity across Unity, Jonglei, Warrap, and Upper Nile states, aligned with seasonal flood dynamics. Key strategic directions include: supporting incremental diversification (e.g., integrating fishing, seasonal agriculture, and small-scale trade) that complements rather than displaces livestock-based livelihoods; investing in locally appropriate aquaculture and flood-recession farming, coupled with extension services, seed systems, and community-based water management; and enhancing market access and value chains, including storage, transport, and cross-border trade linkages, to ensure that diversified activities generate meaningful returns.

Furthermore, the disruption of pastoral transhumance routes by extreme flooding highlights the need for adaptive mobility systems and conflict-sensitive resource governance (Table 17A: *Mobility, migration, and conflict-sensitive adaptation*; Table 17B: *safe mobility corridors, shared resource governance, and negotiated access frameworks*). Key strategic directions

include: Embedding livelihood interventions within conflict-sensitive programming, recognizing that resource competition and livelihood shifts can exacerbate tensions; strengthening adaptive pastoralism, rather than replacing it—through improved veterinary services, mobile animal health systems, flood-resilient grazing strategies, and negotiated access to dry-season pastures; and Strengthening inter-community cooperation through principles of commons governance can enhance equitable access to critical resources such as grazing land, fishing areas, and dry-season refuges.

Lastly, the study emphasizes institutional strengthening and inclusive governance (Table 17A: *Governance and institutional coordination*; Table 17B: *integration of scientific and indigenous knowledge, participatory planning, and decentralized decision-making*). The limited involvement of local communities in planning and water resource management currently undermines resilience. Embedding Indigenous knowledge and customary governance structures into formal systems is essential for sustainable adaptation. Ultimately, these interconnected policy domains position the Sudd as a managed socio-ecological system, where resilience emerges from aligning human activities with, rather than against, flood dynamics.

Critical implications for future options in the Sudd region (policy-linked synthesis)

The implications of this study—and the policy architecture outlined in Tables 17A and 17B—point to a set of critical strategic choices for the Sudd region. As flood risks intensify and exposure expands, some areas are becoming increasingly unsuitable for permanent habitation.

This necessitates a dual approach that combines in-situ adaptation (through the policy pillars above) with mobility-based strategies, including both forced and planned migration.

Forced migration in the Sudd region (policy gap scenario)

Projected increases in flood exposure across the assessed counties indicate that, in the absence of effective policy implementation (Tables 17A–17B), many communities will face forced migration. High vulnerability, limited adaptive capacity, and weak institutional support systems exacerbate this risk. In this context, forced migration reflects a failure of coordinated policy action across key domains—particularly early warning systems, spatial planning, and livelihood adaptation. Without these interventions, recurrent and severe flooding is likely to render settlements uninhabitable, compelling reactive and unplanned displacement.

Planned migration in the Sudd region (policy-driven pathway)

Planned migration represents a proactive and policy-aligned response, directly linked to the pillar on mobility, migration, and conflict-sensitive adaptation (Table 17A) and its operational pathways (Table 17B). The study's findings provide a robust evidence base for integrating migration into long-term development and spatial planning frameworks. By identifying high-risk zones—based on projected population exposure, flood frequency, and proximity to water bodies—governments can implement risk-informed rezoning and relocation strategies. In highly vulnerable counties (e.g., Fangak, Akobo, Twic East, Bor, Rubkona, Mayendit, Leer,

Guit, Koch, Maiwut, Ulang, Longochuk, and Nasir), planned migration may be necessary to avoid recurrent humanitarian crises. This approach aligns with multiple policy pathways in Table 17B and can be operationalized through:

I) Proactive institutional planning. (Table 17B: *risk mapping, relocation frameworks, and intergovernmental coordination.*)
II) Community-led decision-making. (Table 17B: *participatory governance and inclusion of traditional authorities.*)
III) Provision of resilient infrastructure and services. (Table 17B: *climate-resilient settlements and service delivery systems.*)
IV) Integration of climate resilience into new settlements. (Table 17B: *forward-looking planning based on future risk projections.*)
V) Managed retreat in extreme exposure zones. (Table 17B: *targeted relocation from areas with 70–100% exposure during major flood events.*)

Crucially, planned migration must extend beyond physical relocation to address social, cultural, and identity dimensions, as emphasized under the governance and livelihood pillars. Supporting displaced populations requires investments in social integration, preservation of cultural identity, and conflict-sensitive engagement with host communities.

In conclusion, the alignment between empirical findings and Tables 17A–17B demonstrates that resilience in the Sudd region depends on coordinated, multi-sectoral policy implementation. The choice is not simply between staying and leaving, but between unplanned, crisis-driven displacement and strategic, policy-guided adaptation and mobility.

7.4.4 Community level implications

At the community level, the recommendations emphasize empowering households and local institutions as primary agents of resilience. As the field study reveals no efficient mechanisms or strategic investments in place to enable communities in the Sudd region to cope with the existential impacts of flooding, or to adjust to new socio-economic lifestyles in towns or IDP camps. Instead, the current responses, mostly by international non-profit organizations, are organized around temporary emergencies. Approaches that shift away from emergency responses to address chronic, long-term human impacts can provide more humane, purposeful responses to extreme flooding in some locations across the Sudd region. This entails community-led early warning dissemination, utilization of flood hubs for safety and services, and adoption of flexible land-use and mobility practices that reduce conflict and exposure. It also requires integrating traditional ecological knowledge with modern climate information, engaging with mobile service systems, protecting local ecosystems, and diversifying livelihoods to spread risk.

Migration in response to extreme flooding has far-lasting effects on the viability of communities, clans, and families. These personal and social issues are important for the wellbeing of the communities, and they need to be integrated into flood interventions by authorities and their partners. A bottom-up approach is needed to build local adaptive capacity. The local authorities should ensure resources are provided for IDPs that go beyond the physical and economic dimensions to address personal, social, and cultural losses inherent during flood events in the Sudd wetland. Participation in local accountability mechanisms and relocation planning ensures that adaptation remains participatory and context-sensitive, ultimately

grounding resilience in social networks, local knowledge, and collective decision-making capacity.

7.5 Future research

7.5.1 Opportunities for improved conceptualizations

The Sudd remains a "data-scarce" environment in the literature, presenting several promising frontiers for future research that integrate innovative methods with emerging theoretical frameworks. One key opportunity lies in coupled socio-hydrological modeling. A major gap in existing studies is the tendency to treat human systems and hydrological processes as separate, rather than interconnected. Future research could examine how flood-driven migration and settlement decisions reshape hydrological dynamics through land-cover change or infrastructure such as dykes. Agent-Based Modeling (ABM), when coupled with hydrological models, offers a powerful approach to simulate how individual household decisions aggregate to influence the broader landscape. Foundational work by Sivapalan et al. (2012) and Di Baldassarre et al. (2013) provides a strong conceptual basis for exploring these human–water feedback systems. Another important research direction involves the economic valuation of ecosystem services, particularly the Sudd's role as a natural "sponge." Currently, there is a lack of peer-reviewed economic evidence demonstrating how the wetland contributes to downstream water regulation and potential cost savings for countries such as Sudan and Egypt. Without assigning a quantifiable economic value, the Sudd risks being perceived merely as a zone of water loss. Methods such as the Replacement Cost Method or Choice Experiments

could be used to estimate the financial value of its storage and buffering capacity, building on frameworks established by Mitsch and Gosselink (2015) and Costanza et al. (2014).

7.5.2 Opportunities for advancing methodologies

One avenue for future study is the use of remote sensing to better understand flood-recession agriculture. Although it is known that communities cultivate land as floodwaters recede, there is limited data on the productivity and national food security potential of this practice. Applying Net Primary Production (NPP) modeling using satellite imagery from Sentinel-2 and Landsat-9, along with vegetation indices such as NDVI and EVI, could help quantify agricultural yields in these transitional zones. Prior studies by Benansio et al. (2022) and Bunting et al. (2018) provide useful methodological guidance for this type of analysis. Lastly, research into the conflict–water nexus offers a critical but underexplored perspective. There is currently insufficient empirical evidence linking flood dynamics to localized conflict patterns in South Sudan. Spatial econometric techniques, particularly geographically weighted regression, could be used to overlay flood extent data with conflict event datasets such as Armed Conflict Location & Event Data (ACLED). This would allow researchers to test whether areas experiencing displacement or environmental stress are more prone to violence. Relevant methodological approaches have been demonstrated in studies by (Ide et al., 2020), which explore the complex pathways connecting climate variability and conflict at local scales.

7.5.3 Key directions for future research

A future field study conducted from a regional scale approach would capture full implications of the dynamics of cross-border pastoral and population flood related migration between South Sudan and countries such as Uganda, Kenya, Ethiopia, DRC, and Sudan. Analysis of empirical data indicates that local communities aspire to live in proximity with water, but in drier and higher grounds in their native land adjacent to the Sudd. Furthermore, field visits reveal that the local communities are seeking sustainable solutions that support the social system and water system to co-evolve with neither threatening the other. To meet the aspirations of the local communities, future research should build on this study by modelling and empirically testing a range of sustainable interventions, including “soft” solutions (such as community-based adaptation, governance reforms, early warning systems, and livelihood diversification) and “hard” solutions (including flood protection infrastructure, engineered drainage systems, and climate-resilient transport and settlement planning).

Lastly, future geospatial studies should develop a dynamical agent based model for the Sudd region. Such a computational modeling approach simulates the behavior and interactions of individuals as autonomous entities (agents) within the Sudd-Socio-hydrological system over time. The "dynamical" model would represent an evolution of the socio-hydrological system and the agents' states and behaviors through time in the Sudd.

7.6 Concluding remarks

Five years ago, I embarked on this journey with a resolute heart to map the rising waters of the Sudd through the cold, objective lens of geospatial science. Yet, as a child of this land, I have always known that the Sudd Nile is not merely a hydraulic variable to be modeled—it is the lifeblood and the arbiter of our survival. This thesis is rooted in the rhythmic pulse of the Sudd—the seasonal rise and fall of the Nile that shaped my upbringing and now defines my research.

This thesis has been a long-term dream to translate the lived reality of my people into a language the world and our government can no longer ignore. But beyond the maps of hazard, vulnerability, exposure and the data on displacement lies a personal manifesto for our future. We must stop fighting the water and start learning to live with it.

The 'socio-hydrological' future I envision for South Sudan is one where our policy is as fluid and adaptive as the river itself. It is a future where a pastoralist's migration is protected by law, where a school stays dry because it was built with local wisdom and satellite precision, and where our wetlands are recognized not as 'wastelands' to be drained, but as a global treasure and the lungs of the Nile Basin.

For too long, the fragility of our state has been mirrored by the fragility of or lack of our flood defenses. This research proves that resilience is not found in concrete alone, but in the strength of the local communities, the transparency of our governance, and the courage to cooperate with our neighbors.

As I close this chapter of my long academic journey, I open a lifelong commitment to the Sudd. To my fellow South Sudanese, the Nile will continue to rise and fall, but through science, empathy, and evidence-based action, we will no longer be victims of its rhythm. We will instead become its stewards, navigating the floodwaters toward a horizon of stability and peace in the Sudd region and South Sudan.

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CHAPTER 8

8 APPENDIX: AUTHORSHIP STATEMENTS

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To whom it may concern,

I, Prof. Jim W. Hall, certify that Deng Majok Chol completed the majority of the work in the journal articles below, which form part of his DPhil thesis.

1. Chol, D. M., Hall, J. W., Wheeler, K. G., Bernhofen, M., Di Vittorio, C. A., & Strzepek, K. M. (2026). Geospatial analysis of population exposure to flooding in the Sudd Region, South Sudan.
2. Chol, D.M., Wheeler, K.H., Paszkowski, A., Smith-Kroll, S. and Hall, J.W. Dynamics of human adaptation to flood risk in the Sudd wetlands, South Sudan.
3. Chol, D. M., Strzepek, K. M., and Hall, J.W. Impact of flood risk on migration in South Sudan: a historic and climate change assessment of the Sudd.

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