



Lake Victoria to the Sudd Wetland: flood wave timing, connectivity and wetland buffering across the White Nile

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Abstract. The White Nile from Lake Victoria through Lakes Kyoga and Albert to the Sudd forms a complex lake-river-wetland corridor where flood propagation, storage, and attenuation remain poorly quantified. Following unprecedented and persistent flooding across South Sudan in 2022, this study quantified how long it takes a flood wave to travel from Lake Victoria to the Sudd and how upstream storage and connectivity shape multi-year flood behaviour. Using daily lake levels, discharge, CHIRPS rainfall, and MODIS-derived inundation for 2002–2024, we tracked sequential flood peaks through the Victoria–Kyoga–Albert–Sudd cascade and mapped monthly wetland dynamics across five South Sudan sub-catchments. Flood-wave tracking showed a mean system transit time of 16.84 ± 1.95 months (range 13.0–20.9 months), overturning the long-held assumption of a five-month propagation. Segmental analysis revealed rapid transmission from Victoria to Kyoga (mean 4.2 months) but strong attenuation through the Albert–Sudd reach (mean 9.3 months), consistent with extensive floodplain storage and backwater control. Correlations between Lake Victoria peaks and downstream wetland extents strengthened markedly after 2019, with r^2 exceeding 0.8 at 9–13-month lags, confirming strong hydraulic coupling and long system memory. The 2019–2024 high-water regime was therefore not a series of isolated rainfall events but a multi-year propagation of excess storage initiated by the 2019 positive Indian Ocean Dipole anomaly and consecutive rainfall seasons. When compared with historical episodes in the 1870s and 1960s, the persistence and spatial reach of the 2019–2024 floods rank among the most extensive in the modern record. These results redefine the White Nile as a long-memory system where upstream storage governs downstream flood risk, offering a new empirical basis for flood forecasting, wetland management, and anticipatory action in South Sudan and the wider basin.



Keywords. White Nile, Sudd Wetland, floodwave propagation, lake-wetland connectivity, flood attenuation, transit time, hydrological memory, flood forecasting, early warning.

1 Background and Motivation

35 The White Nile from Lake Victoria through Lakes Kyoga and Albert to the Sudd is a complex system with complex hydrology, where flood timing and magnitude are governed by lake-river-wetland coupling; storage, lateral movements and dispersion, tributary exchanges, vertical water exchanges with groundwater and backwater effects (Sutcliffe & Parks, 1999; Vanderkelen et al., 2018a, 2018b). Within this system, the Sudd, Africa's largest and the world's second-largest freshwater wetland, plays a critical role by regulating downstream flow through strong storage and evaporation and pronounced attenuation of flood waves (Ramsar Secretariat, 2006; Rebelo et al., 2012; UNESCO, 2017). Acting as a natural sponge, the wetland absorbs and delays upstream floodwaters and in turn buffers downstream reaches during high-flow periods (Kadykalo & Findlay, 2016; Mohamed et al., 2005b, 2005a). Empirical and modelling studies of the Sudd wetland document multi-month lags between inflow and outflow and substantial water losses to evaporation and internal storage that reshape the downstream water budget and local hydroclimate, and they also highlight the difficulty of simulating inundation reliably in tropical wetlands (Marthews et al., 2022; Mohamed et al., 2005b, 2005a; Mohamed & Savenije, 2014; Sutcliffe & Brown, 2018; Sutcliffe, 1974). Additional complexity arises at and below Malakal, where the Bahr el Ghazal and the Sobat-Baro-Akobo systems join, adding low-gradient floodplains and distributary wetlands that further modulate hydrograph shape and persistence (Rebelo et al., 2012; Sutcliffe & Parks, 1999). Framing the Sudd within this chain, we treat it first as a whole for basin context, then resolve South Sudan sub-catchments to expose how a complex system with complex hydrology transmitted and transformed flood peaks during 2020–2024.

Across the historical record, Lake Victoria water levels typically reach their annual maxima around May, following the March–May long-rains season, whereas peak flooding in South Sudan tends to occur between September and October during the JJAS rainfall period (Nicholson, 2017a; Sutcliffe & Parks, 1999). This four-to-five-month seasonal offset led to a widely held but untested assumption that flood propagation from Lake Victoria to the Sudd occurs within roughly five months. This assumption became embedded in operational hydrological interpretations and flood-related decision making, often serving as a planning rule-of-thumb for anticipating downstream flood timing. However, no published study has explicitly quantified this system-wide travel time. Existing literature describes phase differences (Nicholson, 2017a; Sutcliffe & Parks, 1999) and storage-controlled attenuation between the lakes and wetlands (Mohamed et al., 2005a, 2005b; Mohamed & Savenije, 2014; Sutcliffe & Brown, 2018; Williams, 2018) but stops short of defining how long it actually takes a floodwave to travel from Lake Victoria through Kyoga and Albert to the Sudd. Addressing this gap is central to understanding basin connectivity, memory, and the persistence of recent flooding across South Sudan.



Beginning in 2019, the Sudd experienced a sequence of extreme floods that departed from recent norms. Satellite analyses and field reports show a step-change expansion and unusually persistent inundation through 2019–2021, with floodwater remaining during normally dry months and priming the system for the record extent in 2022 (Caldwell, 2022; Hardy et al., 2023; Marthews et al., 2022; UNHCR, 2022). Notably, the 2022 peak occurred despite suppressed rainfall across parts of East Africa in 2022, which underscores the role of multi-year storage and long memory in this complex system with complex hydrology (KMD, 2022; UNMA, 2022; WMO, 2023). In 2020, Lake Victoria reached a historic high after a rapid 1.44 m rise between September 2019 and May 2020, driven by above-average precipitation and tributary inflow, with attribution analysis indicating that anthropogenic climate change likely increased both the probability and magnitude of that event (Pietroiusti et al., 2024). When the Sudd is saturated, slow drainage and high storage capacity can sustain or amplify flooding even in years with near-normal or below-normal local rainfall (Lamberts, 2009; Mohamed et al., 2005b; Sutcliffe, 1974). Earlier studies further note the substantial attenuation and long lake memory within the White Nile and Sudd Wetland system, which when compounded suggest transit times potentially exceeding one year (Sutcliffe & Parks, 1999; Williams, 2018).

Comparing 2019–2024 with past episodes helps show how exceptional the flooding was. Multi-year wet spells and high White Nile flows are part of the system’s natural variability, with notable episodes in the 1870s, late 1910s, and early 1960s, including the 1961–1964 rise of Lake Victoria by about 2.5 m that propagated downstream for years (Hurst & Phillips, 1938; Nicholson, 2017a; Nicholson & Yin, 2001; Sutcliffe & Parks, 1999). Among these, the reconstructed flood of the 1870s appears to have been the most extreme (Nicholson & Yin, 2001). During such periods the Sudd expands markedly, retains water for months, and alters downstream regimes well beyond the cessation of rainfall (Mohamed et al., 2005a; Sutcliffe & Brown, 2018). This historical framing shows that compound, persistent flooding is possible within the White Nile system, while highlighting the amplifying roles of antecedent wetness, wetland retention, and delayed drainage in flood duration and severity.

The 2019 positive Indian Ocean Dipole event, one of the strongest on record, contributed to exceptional 2019 short-rains totals across East Africa and set up high lake levels into 2020, compounding downstream flood risk (Wainwright et al., 2021). Variability from ENSO and the IOD modulates regional rainfall on interannual scales, while long-term climate change is projected to increase the odds of extreme precipitation and flood hazards in many tropical basins, including eastern Africa (Hirabayashi et al., 2013; IPCC, 2021). Recent work on Lake Victoria’s 2019–2020 extremes further indicates a climate-change footprint on both over-lake rainfall and basin inflows, strengthening the case that baseline flood risk in the White Nile is shifting (Pietroiusti et al., 2024).

Anecdotally, these floods have been described as unprecedented in Unity, Jonglei, and Upper Nile states of South Sudan with the scale and persistence of inundation not seen before in living memory (Pal Mai Deng, Minister of Water Resources and Irrigation, personal communication, May 2024). Several humanitarian impacts were recorded with more than 835,000 people affected in 2021 alone, large areas of settlement remaining inundated for months, and major disruptions to transport, water,



education, and healthcare services (Caldwell, 2022; UNHCR, 2022). Global and national early warning systems struggled with the duration and compound nature of these floods. Anticipatory action pilots, which are based on pre-agreed early measures triggered by forecast thresholds before an event (Chaves-Gonzalez et al., 2022; Coughlan De Perez et al., 2015, 2016; IFRC, 2022; Stephens et al., 2015), were attempted but faced limitations in data, lead time, and forecast performance over South Sudan (Alfieri et al., 2024; Caldwell, 2022; Easton-Calabria, 2024).

The underlying drivers of these multi-year extreme floods characterised by slow flood wave propagation, saturation thresholds, backwater effects, and storage-dominated lags which can extend responses well beyond a single wet season and blur the link between local rainfall and downstream inundation, are not fully understood. This motivates a system-scale framing that examines transit times, attenuation, and interannual memory from Lake Victoria through Kyoga and Albert to the Sudd and its South Sudan sub-catchments.

Existing hydrological studies across the White Nile provide essential foundations in water balance, flow regimes, seasonal variability, and climate influence, yet much of the literature treats components in isolation rather than as a single connected White Nile system. Lake Victoria-only water-balance studies are foundational (Awange et al., 2008; Gibb, 1984; Hurst & Phillips, 1938; Kite, 1982; Mistry & Conway, 2003; Mugume et al., 2024; Pietroiusti et al., 2024; Sene, 2000; Swenson & Wahr, 2009; Vanderkelen et al., 2018a, 2018b); reach-scale analyses treat the Victoria Nile through Lake Kyoga as a separate unit (Brown & Sutcliffe, 2013; Hurst & Phillips, 1938; Sutcliffe & Parks, 1999); separate studies focus on Lake Albert and the Albert Nile reach (NBI, 2008; Sutcliffe & Parks, 1999); wetland-focused work examines the Sudd (Conway & Hulme, 1996; Dong et al., 2024; Hardy et al., 2023; Lamberts, 2009; Mohamed et al., 2005b; Mohamed & Savenije, 2014; Rebelo et al., 2012; Sutcliffe & Brown, 2018; Sutcliffe, 1974; Williams, 2018); and a large body of research concentrates on the fast-response Blue Nile (Conway, 2000; Conway & Hulme, 1996; Rientjes et al., 2011; Tekleab et al., 2011, 2013). As a result, basin-wide slow flood wave propagation, threshold-driven wetland expansion, backwater controls, and storage-dominated dynamics remain weakly evidenced in the published record since most studies focused on individual reaches or lakes. The unprecedented Sudd extent in 2022, despite suppressed regional rainfall signals in parts of East Africa, is therefore not well explained by frameworks that prioritise local rainfall alone, pointing instead to antecedent lake levels, wetland saturation, and cumulative storage (Marthews et al., 2022; Pietroiusti et al., 2024; WMO, 2023). In response, our study treats the Victoria–Kyoga–Albert–Sudd system as one connected complex corridor with complex hydrology, then resolves South Sudan sub-catchments within that system to quantify flood wave timing, attenuation, and interannual memory.

Moreover, hydrometeorological observations, particularly, across South Sudan remain sparse and discontinuous because conflict over the years which disrupted observation station networks. Several studies have relied on merged station-satellite products to compensate for gauge scarcity (Dinku et al., 2007, 2018; Gebrechorkos et al., 2018). In the absence of ground wetland-extent observations, satellite products partly fill the gap but cloud and sensor limits still leave blind spots, especially



over the Sudd (Lin et al., 2019; Pekel et al., 2016; Rebelo et al., 2012). Lake Victoria outflow records are not publicly available, so many water-balance studies infer releases from the Agreed Curve or related reconstructions without the directly observed Lake Victoria discharge contribution through releases in Jinja (Pietroiusti et al., 2024; Sene, 2000; Vanderkelen et al., 2018a).

135 Taken together, sparse gauges, satellite blind spots, and unavailable Lake Victoria outflow records constrain basin-wide attribution of drivers and impede precise quantification of flood wave propagation, storage, and timing across the White Nile.

In light of basin-wide observational gaps; limited quantification of travel times, storage, attenuation, and floodplain exchange; insufficient sub-catchment resolution; weak separation of upstream forcing from local rainfall; missing Lake Victoria outflow
 140 records; and poor flood-forecast skill that hindered anticipatory action, this study investigates why there was unprecedented flooding in South Sudan in 2022. The analysis followed four steps that build from context to mechanism. First, we contrasted pre-2019 and 2019–2024 regimes for Lake Victoria and the Sudd to position the recent floods within the long-term historical variability. Second, we traced the propagation of flood peaks from Lake Victoria through Lakes Kyoga and Albert into the South Sudan sub-catchments, overlaying rainfall anomalies to test whether local rainfall or upstream inflow dominated. Third,
 145 we quantified connectivity between the upstream lakes and downstream wetlands using lag-correlation and persistence analyses to capture how hydrological memory and backwater effects shaped flood timing and extent across sub-catchments. Finally, we mapped monthly wetland extents to visualise spatial progression, activation pathways, and the geometry of connected flood parcels across the Sudd. The study is guided by the following objectives:

- i. Contextualise Lake Victoria levels and Sudd extent of the 2020–24 flood event relative to the historical record.
- 150 ii. To establish the variation in transit time of the flood wave along the White Nile, comparing 2022 and the historical behaviour.
- iii. To evaluate sub-catchment-scale correlations and hydrological connectivity between the upstream lake system and South Sudan wetlands during the high-lake level phase.
- iv. To map spatial patterns of flood persistence and channel activation within the Sudd wetland during extreme
 155 flooding.

1.1 Study Area

This study focuses on the White Nile system from Lake Victoria in Uganda to the Sudd Wetland in South Sudan, encompassing a hydrologically complex integrated river-lake-wetland system segmented into three key reaches between the major lakes and Sudd wetland: Victoria–Kyoga, Kyoga–Albert, and Albert–Sudd. This segmentation reflects sharp transitions in flood wave
 160 behaviour, from rapid lake outflows to highly attenuated lake and wetland responses, governed by nonlinear processes such as storage, dispersion, and tributary inflow interactions.

Special emphasis is placed on the Albert–Sudd segment, which includes a geomorphologically diffuse transition zone between the unregulated outflow of Lake Albert and the expansive Sudd Wetland. These sections are characterized by extended wetland



165 interaction and multiple lake-like floodplain sinks, particularly along the Albert Nile corridor from Lake Albert exit at Pakwach
 Bridge to the Uganda–South Sudan border. This corridor includes swamp-dominated zones in Obongi District, where
 floodwaters often spread laterally across a broad floodplain, including areas such as Rhino Camp refugee settlement. Swamp-
 dominated river sections are prone to extensive lateral connectivity during high-flow periods, promoting floodplain storage,
 hydrodynamic diffusion, and delayed downstream routing (Sutcliffe & Parks, 1999; Williams, 2018).

170 Catchment boundaries were delineated using HydroSHEDS level 4–6 sub-basins (Lehner & Grill, 2013) and cross-referenced
 against national hydrological planning frameworks to ensure alignment with management-relevant units. Specifically,
 Uganda’s Water Management Zones (MWE, 2009), and South Sudan’s Irrigation Development Master Plan (MEDIWR, 2015)
 were used to validate and refine sub-catchment definitions, particularly where sub-national boundaries influence rainfall
 175 aggregation and flood response assessment. These delineations allowed for the spatial aggregation of rainfall data and flood
 responses in hydrologically coherent units, guiding upstream-downstream analysis. Fig. 1 illustrates the layout of the sub-
 catchments, major lakes and rivers, Sudd wetland and key observation stations.

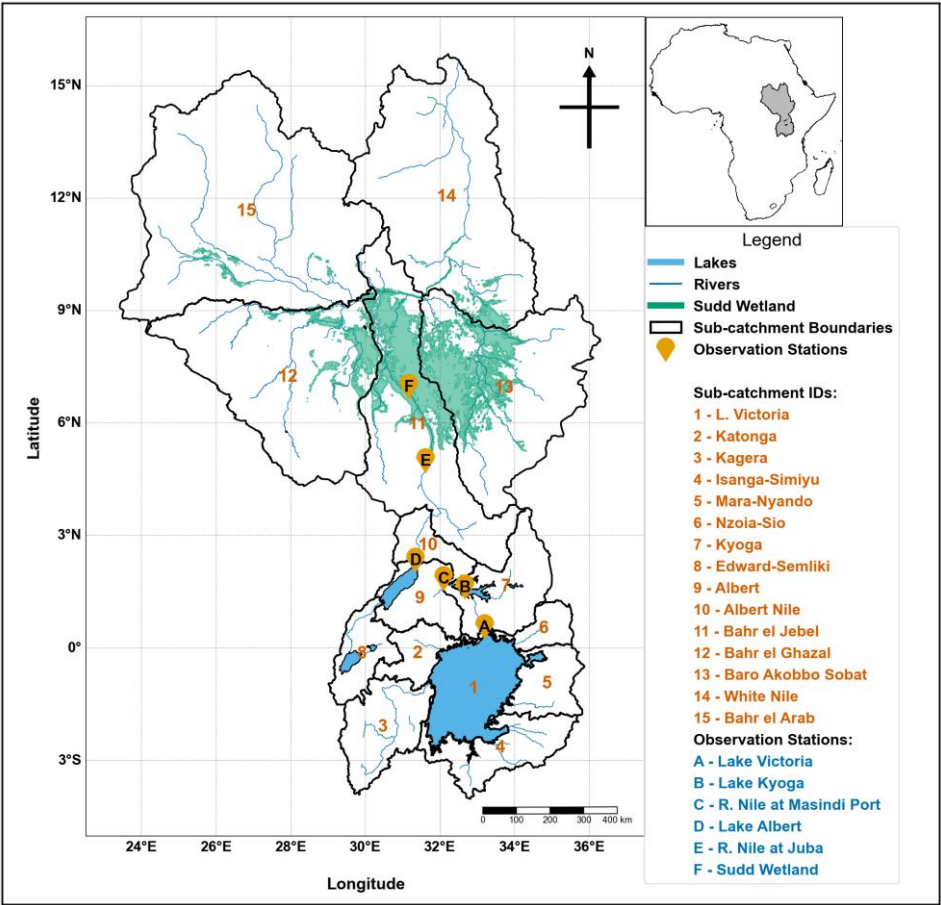
Sub-catchments 2 to 6 drain into Lake Victoria (sub-catchment 1), which was treated as a standalone sub-catchment given its
 180 dominant upstream role and substantial direct rainfall input that falls over it. Victoria, whose outflows at Jinja are regulated
 under the Agreed Curve (Kull, 2006), drains northwards into Lake Kyoga (sub-catchment 7), which receives both upstream
 inflow and local rainfall. In turn, Kyoga drains into Lake Albert with additional direct rainfall inputs from sub-catchments 8
 and 9. The shores of Lake Kyoga and its satellite water bodies are surrounded by extensive swamp and wetland systems (e.g.
 about 4,510 km² of swamp adjacent to ~1,760 km² open water) (Brown & Sutcliffe, 2013), often dominated by papyrus and
 185 aquatic vegetation (Ma et al., 2024; NEMA, 2008). These three lake basins were analysed as independent hydrological basins,
 each with distinct tributary inflows and internal storage dynamics.

Further downstream, sub-catchments 10–15 generate rainfall-driven inflows into the Sudd Wetland through a network of
 tributaries from multiple directions. The main Nile channel flows through the Bahr el Jebel (11) sub-catchment. Notably, the
 190 Sudd lies within a broad paleo-lake depression, often hypothesized as the remnant of a large “Megalake Sudd” (Álvarez, 2023;
 Sutcliffe & Parks, 1999). This topographic setting reflects earlier drainage reorganizations, including Neogene reversals when
 the upper Nile drained westward toward the Congo before being captured northward into its present course (Abdelsalam, 2018;
 Holzförster & Schmidt, 2007; Issawi & Farouk, 2023; Stankiewicz & de Wit, 2006). This paleo-lake topography around the
 Sudd facilitates channel activation of the braided rivers within the wetland resulting in lateral movement and backwater effects
 195 between adjacent sub-catchments (Mertes, 1997; Sutcliffe & Parks, 1999). Consequently, although the sub-catchments
 connected to the Sudd Wetland are treated as indicative units, the wetland’s complex hydrology departs from classical



catchment behaviour and during high inflows, wetland activation facilitates lateral spillovers across nominal boundaries of adjacent sub-catchments.

200 This spatial framework underpins the flood wave segmentation used in this analysis (Victoria–Kyoga, Kyoga–Albert, Albert–Sudd) which supports a coherent structure for assessing upstream-downstream hydrological linkages.



205 **Fig. 1: Map of the White Nile Basin showing delineated sub-catchments, lakes, major rivers, and the Sudd Wetland extent. Sub-catchments are labelled numerically (1–15) with names listed in the legend. Observation stations (A–F) mark key hydrological data collection locations used in this study: Lake Victoria (A), Lake Kyoga (B), River Nile at Masindi Port (C), Lake Albert (D), River Nile at Juba (E), and the Sudd Wetland (F). Background river networks and sub-catchment boundaries are derived from the HydroSHED dataset, and wetland extent is based on MODIS flood mask composites. The map is projected in geographic coordinates (EPSG:4326) with a graduated scale bar for accurate distance representation using UTM Zone 36N.**

210 **2 Data and Methods**

This section outlines the data sources, study design, and analytical framework used to investigate flood wave propagation along the White Nile system. The analysis tracks the flow of water from Lake Victoria in Uganda through Lakes Kyoga and



Albert into the Sudd Wetland in South Sudan. To highlight downstream flood anomalies, we also assess responses in key South Sudan sub-catchments adjacent to the main Nile channel that experienced severe inundation between 2019 and 2024. Beyond tracking the flood wave, the analysis quantifies timing, connectivity, and storage dynamics across the lake-river-wetland system.

Sect. 2.1 describes the datasets used, while Sect 2.2 to 2.7 detail the methodological steps: comparative hydrological benchmarking between Lake Victoria and the Sudd Wetland (2.2); assessment of the seasonality of annual maxima across Lakes Victoria, Kyoga, and Albert (2.3); rainfall anomaly analysis (2.4); flood wave event detection and lag estimation (2.5); linking Lake Victoria annual maxima to downstream wetland extent in South Sudan sub-catchments (2.6); and flood-persistence mapping to track Sudd Wetland activation (2.7).

2.1 Data

We compiled rainfall, hydrological, and flood extent datasets with temporal resolutions from daily to dekadal for this study.

2.1.1 Rainfall Data

Due to sparse and uneven gauge coverage across Uganda and South Sudan, and documented issues in East African station networks such as outages, inconsistent reporting, and metadata gaps (Bamweyana et al., 2021; Dinku et al., 2007; Thiemi et al., 2012), we treated rainfall ground observations as insufficient for basin-wide analysis. We therefore used CHIRPS to supply spatially complete rainfall estimates. CHIRPS produces daily 0.05° estimates from 1981 to present by blending infrared satellite retrievals with available station data, improving local bias where gauges exist while maintaining coverage over gauge-poor areas (Funk et al., 2015). Across East Africa, validations targeting hydrologically relevant properties, including the seasonal cycle, spatial rainfall patterns, wet-day frequency, and the timing and volume of heavy-rain events; CHIRPS reproduced these features and ranked among the best daily-scale products in Ethiopia, Kenya, and Tanzania (Dinku et al., 2018; Gebrechorkos et al., 2018; Thiemi et al., 2012). In Uganda, monthly agreement with gauges was high (Bamweyana et al., 2021). Evidence for South Sudan was limited with only five operating long-term stations available for recent evaluation, and records at key sites such as Juba, Malakal, Raga, Renk, and Wau contained substantial gaps (Basheer & Elagib, 2019; Zakaria Lukwasa et al., 2022). CHIRPS has nonetheless been used operationally for subnational rainfall indicators in South Sudan, although formal, country-specific validation studies are few (Humanitarian Data Exchange, 2025). These validations supported the use of CHIRPS as the robust primary rainfall input for this study.

2.1.2 Hydrological Data

Daily river discharge and lake water levels were obtained from the Directorate of Water Resources Management (DWRM, Uganda). To place the 2019–2024 floods within the broader hydrological context of the White Nile system, we compiled long-term Lake Victoria records from 1950 to 2024. For the most recent decade, in which gauge data for Lake Victoria were not



readily available from DWRM, the series was extended by gap filling with satellite altimetry from NASA’s Global Water Monitor lake-level portal (<https://earth.gsfc.nasa.gov/gwm/lake/>). This portal provides a 10-day multi-mission record suitable for anomaly screening and gap filling (NASA, 2025). Discharge records for the South Sudan sections of the Nile were obtained from the Ministry of Water Resources and Irrigation (South Sudan).

2.1.3 Flood Extent Data

Flood extents for South Sudan, and the Sudd Wetland in particular, were derived from MODIS-based inundation masks produced and post-processed by the World Food Programme (WFP). These products apply a water-detection algorithm to satellite surface reflectance composites at 10-day intervals, combined with cloud filtering and temporal smoothing to improve consistency. The resulting dataset provides spatially continuous records of wetland and floodplain dynamics in the Sudd from 2002 onward. For this study, we retained the WFP product as provided, consistent with published MODIS near-real-time flood-mapping practices (Lin et al., 2019; Ticehurst et al., 2014), and used it to quantify wetland expansion-contraction cycles and extract sub-catchment-level flood extents for 2002–2024.

Table 1: Summary of the datasets used, their resolution, and application.

Variable	Dataset	Source	Resolution	Purpose
Elevation	Copernicus GLO-30 DEM	ESA via OpenTopography (ESA, 2024)	30 m	Generation of the White Nile longitudinal profile to contextualize flood wave timing and lag interpretation
Precipitation	CHIRPS	Climate Hazards Group (https://www.chc.ucsb.edu/data/chirps)	Daily; 0.05°	Rainfall accumulation and timing analysis
Lake Levels	Observed Lake Levels	DWRM (Uganda)	Daily	Peak timing and hydrograph shape
Lake Level Altimetry	NASA Global Water Monitor (GWM)	NASA (https://earth.gsfc.nasa.gov/gwm/lake/)	~ 10- day	Gap filling and data anomaly detection
River Discharge	Observed flow	DWRM (Uganda); MWR&I (South Sudan)	Daily	Peak timing and hydrograph shape
Wetland and sub-catchment inundated extents	MODIS-derived flood masks	World Food Programme (WFP)	~ 10- day	Sudd Wetland and sub-catchment level flood extents
Catchment Boundaries	HydroSHEDS; National Water	HydroSHEDS; National agencies	Vector	Catchment definitions & Rainfall spatial aggregation



	Resources Layers (vector)			
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2.2 Comparative Hydrological Benchmarking (Lake Victoria and the Sudd Wetland)

To place recent floods in historical context, we benchmarked Lake Victoria levels and Sudd Wetland extents. Lake Victoria records (observed gauge data extended with NASA’s Global Water Monitor altimetry) and Sudd extents (MODIS-derived inundation from WFP) were separated into two periods: pre-2019 and 2019–2024. The decision to split the data periods that way is informed by the 2019 positive Indian Ocean Dipole (IOD) event and the resulting unusually heavy and extended 2019–2020 short rains season (Wainwright et al., 2021) which set the stage for elevated lake levels and persistent wetness that carried forward into subsequent seasons. For each period, peak values were identified and compared.

Hydrographs were then constructed to display both periods together, with horizontal reference lines marking the peak levels. A reconstructed peak from the 1878 flood (1137.3 masl), reported by Nicholson and Yin, (2001), was added to the Lake Victoria record as a long-term historical benchmark. The Sudd was first analysed as an aggregated extent to establish system-scale context; subsequent analyses disaggregate to sub-catchments.

This benchmarking step established a reference frame for evaluating the persistence and magnitude of the 2019–2024 floods relative to earlier variability.

2.3 Seasonality of Annual Maxima in Lake Victoria, Lake Kyoga, and Lake Albert

Long-term changes in the timing of annual maximum lake levels for Lakes Victoria, Kyoga, and Albert, spanning 1950–2024 have been analysed. Daily lake level records were aggregated into hydrological years, defined from March to February, to align with the main rainfall regime in the upper White Nile Basin (Nicholson, 2014; Sutcliffe & Parks, 1999). For each hydrological year, the annual peak was identified as the maximum daily lake level.

The seasonal timing of these peaks was then expressed relative to the hydrological calendar, converted to circular angles, and represented on polar diagrams where the radial dimension corresponded to relative peak magnitude (Fisher, 1995; Jammalamadaka & SenGupta, 2001). Circular mean dates were computed to capture the central tendency of peak timing, while median hydrological days were also calculated as a linear reference.



290 To investigate long-term shifts, peaks were aggregated by decade (1950s through 2020s). For each decade, circular mean peak dates and average magnitudes were computed, and only decades with at least five valid years were retained. The period 2018–2024 was highlighted separately, with individual years plotted in distinct colours with circular markers, to contrast recent anomalies against historical variability.

295 This approach provided both a long-term baseline of seasonality and a detailed perspective on recent years when extreme wet conditions and widespread flooding were reported across the White Nile system (Pietroiusti et al., 2024; Tate et al., 2004; Vanderkelen et al., 2018a, 2018b).

2.4 Rainfall Anomaly

300 Daily precipitation anomalies were quantified using the Standardized Precipitation Index (SPI) (Guttman, 1999) computed at a 180-day accumulation window (SPI-6). SPI-6 rather than shorter windows such as SPI-3 has been adopted to capture the long hydrological memory characteristic of the White Nile system, where rainfall signals can propagate through the series of lakes and wetlands over several months to more than a year (Sutcliffe & Parks, 1999; Williams, 2018).

Daily resolution was used while retaining multi-month memory too by forming rolling 180-day accumulations of daily rainfall.
 305 For each catchment i and day t , the rolling sum was computed following Eq. (1):

$$S_{180,i}(t) = \sum_{k=0}^{179} P_i(t - k) \quad (1)$$

Where $P_i(t)$ is daily precipitation. To avoid unstable values near gaps, a sum was only taken when at least 90 % of the days in the window were available. This retains long-memory signals while guarding against any artefacts in the data.

310 A fixed baseline of 1983–2017 was adopted, spanning the mature satellite era for CHIRPS (Funk et al., 2015) and preceding the recent high-lake period under study. To account for seasonality, each calendar day t was matched to a ± 15 -day pool by day-of-year within the baseline. For example, an SPI-6 value on 10 June is compared against all baseline S180 values falling between 26th May and 25th June. This season-matched pooling prevents mixing fundamentally different wet/dry regimes while still yielding a large sample ($31 \text{ days} \times 35 \text{ years} = 1,085 \text{ observations per pool}$).

315 Within each day-of-year pool, the accumulated rainfall values were fitted to a two-parameter gamma distribution, following the standard SPI procedure. Percentiles were obtained from this fitted distribution and converted to standard normal deviates using the inverse Gaussian transformation (Guttman, 1999). This parametric approach preserves the conventional interpretation of SPI as a normally distributed index of wetness or dryness. SPI-6 time series were computed per contributing
 320 sub-catchment.



Anomalies were visualised using continuous daily SPI-6 heatmaps to highlight temporal persistence and seasonality of wet and dry phases. A diverging colour palette (wet = blue, dry = red) was applied, with reference bands indicating standard SPI categories: severely wet ($\text{SPI} \geq 2.0$), moderately wet ($1.0 \leq \text{SPI} < 2.0$), near-normal ($-1.0 < \text{SPI} < 1.0$), moderately dry ($-2.0 < \text{SPI} \leq -1.0$), and severely dry ($\text{SPI} \leq -2.0$). These categories are provided as interpretive guides rather than formal thresholds (Guttman, 1999).

2.5 Flood wave Event Detection and Lag Estimation

Although MODIS-derived wetland extent began in mid-2002, we retained a 2000 start for the other datasets to capture upstream events that originated before 2002 but produced delayed downstream impacts. We analysed a common window from 2000 to 2024 and aligned all datasets to the Lake Victoria hydrological year.

Flood wave propagation was analysed with an event-based workflow anchored to Lake Victoria, the hydrological origin of the White Nile. Each flood wave was named by the hydrological year, defined here as March to February. To reflect regional hydrological dynamics, we defined the hydrological year as March to February, based on long-term Lake Victoria levels which is the most upstream point in the system; with February typically marking the annual minimum. This followed WMO guidance to adapt hydrological years to local natural flow regimes (WMO, 2020). This groups the March - May long-rains season, the May to early-June lake-level peak, and the September-November short rains within a single accounting cycle, and avoids splitting a single flood wave across two years (Camberlin & Philippon, 2002; Kite, 1982; Vanderkelen et al., 2018a). Downstream segment peaks keep the Lake Victoria event name even when their peaks fall in the next calendar year or the next hydrological year. For each hydrological year, we identified the Lake Victoria peak, then traced the same event sequentially through three segments: Victoria–Kyoga, Kyoga–Albert, and Albert–Sudd Wetland. The MODIS-derived Sudd Wetland extent was disaggregated into five sub-catchments (Bahr el Jebel, Bahr el Ghazal, Bahr el Arab, Baro Akobo Sobat, and the White Nile; see Fig. 1) to examine spatial expansion and timing differences during high upstream lake level periods. Wetland extent was then derived for each sub-catchment, and the sequential analysis was extended to a fourth step linking Lake Albert to the sub-catchments. Subsequent analysis distinguished sub-catchments directly connected to the upstream lakes, for which this approach holds, from those responding primarily through spillover after the connected units. Chronology was enforced such that the downstream peak (DS) identified for a segment served as the upstream (US) reference for the next segment.

2.5.1 Peak Detection and Segmental Tracking

For each hydrological year, the Lake Victoria event was defined as the annual maximum lake level occurring between April and June. This window coincides with the long-rains season and the typical timing of lake-level peaks near May (Camberlin & Philippon, 2002; Nicholson et al., 2021; Vanderkelen et al., 2018b, 2018a). Restricting the search to this period reduces false detections outside the main wet season.



355 A centred 61-day window (± 30 days) around the detected peak was then extracted to represent the upstream event. For each downstream segment, a forward 335-day search window was opened beginning the day after the upstream window ended. This one-year search horizon allows for slow transmission and storage effects while avoiding overlap with the next hydrological cycle.

360 The matched downstream peak became the upstream anchor for the next segment, where a new 335-day window was opened and the search repeated. Chronological consistency was enforced so that a downstream peak labelled year $Y+1$ could not occur earlier than any accepted peak from year Y . Any candidate violating this rule was discarded, and the next best match was evaluated. Years without a valid candidate within the search window were flagged as unmatched and were not propagated further downstream.

365

Within each downstream search window, we first smoothed the times series Q_t with a centered moving average following Eq. (2):

$$\hat{Q}_t = \frac{1}{2w+1} \sum_{i=t-w}^{t+w} Q_i, \quad w = 15 \text{ days}, \quad (2)$$

370 which suppresses short-lived oscillations without redefining event timing (Laaha et al., 2017; Van Lanen et al., 2013; Van Loon & Laaha, 2015). Candidate peaks $\hat{Q}_t$ are retained only if their prominence exceeds a site-specific threshold δ following Eq. (3):

$$Prom(\hat{Q}_p) = \hat{Q}_p - \max(\hat{Q}_l, \hat{Q}_r) \geq \delta \quad (3)$$

375 Where $\hat{Q}_l$ and $\hat{Q}_r$ are the nearest local minima immediately preceding and following the candidate peak on the smoothed series. Prominence was measured relative to the higher of these two minima. Thresholds were tuned once per site after exploratory checks and then held fixed across years to prevent year-specific overfitting and to promote comparability.

From the pool of retained peaks within the downstream search window, we evaluated shape similarity to the upstream template
 380 by comparing centered 61-day, min-max-normalized windows and selecting the minimum root mean square error (RMSE) following Eq. (4):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{Q}_i^{US} - \hat{Q}_i^{DS})^2} \quad (4)$$

Where $\hat{Q}_i^{US}$ and $\hat{Q}_i^{DS}$ are the min-max normalized values of upstream and downstream event hydrographs.

385 If several candidates have near-equal RMSE, we selected the peak with the smallest transit time to preserve chronology and hydrological plausibility and to represent the worst-case fast-moving flood wave scenario which we should plan for in flood



risk management. Years without a valid downstream match were flagged as signal degradation, typically due to flat hydrographs, merged peaks, or strong local forcing at the site. Automated matches were then visually reviewed, and manual adjustments were made only where automated picks clearly contradicted hydrological context, with the smallest change necessary to preserve event identity. This prominence-then-similarity sequence, together with fixed windows and stable thresholds, is adopted to ensure robustness and applicability across basins and years.

We visualised the upstream-to-downstream flood wave tracks by overlaying spline curves on the time series and connecting the matched peaks across segments

2.5.2 Lag Estimation

Once the peaks were identified and matched, segmental lag time was computed for each year i following Eq. (5):

$$Lag_i = t_i^{DS} - t_i^{US} \quad (5)$$

where t_i^{US} and t_i^{DS} are the upstream and downstream matched peak dates. Lags were reported for 2000 to 2024 with segment-wise summaries, and lags for 2019 to 2024 are compared against the 2000 to 2018 baseline to assess departures consistent with the high-lake levels period.

2.5.3 Rainfall Context for Event Interpretation

To place the tracked flood waves in meteorological context, we used CHIRPS rainfall aggregated as 180-day rolling totals, consistent with the SPI-6 accumulation window and the system's long hydrological memory (Funk et al., 2015). Daily CHIRPS values were first averaged spatially over each analysis unit or lake, and where several sub-catchments contributed, an area-weighted mean was used. For visual comparison, these rainfall accumulations were plotted on a secondary axis alongside the flood-wave series for readability.

Rainfall on these plots was included solely for interpretation, allowing comparison of the timing between rainfall inputs and flood-wave responses rather than for quantitative lag estimation. This interpretive use follows earlier studies that examined phase relationships between precipitation and hydrological response across the White Nile system (Mistry & Conway, 2003; Nicholson et al., 2021; Vanderkelen et al., 2018b, 2018a; Yin & Nicholson, 2002).

2.6 Lake Victoria annual maxima and downstream wetland extent in South Sudan sub-catchments

To quantify how the annual Lake Victoria maximum levels relate to wetland extent in South Sudan sub-catchments, correlations are built for each hydrological year. For each hydrological year, as already described in the previous sections of this paper, a single peak date when the Lake Victoria annual maxima occurs is taken as our starting point $t=0$. Flooded areas from MODIS satellite datasets at a dekadal scale are evaluated at fixed lags $t=0$ months to $t=24$ months. Correlations between



420 the Lake Victoria annual maximum and lagged wetland extents are computed separately for 2002 to 2018 and 2019 to 2023 to contrast the longer baseline with recent high-water conditions.

Wetland area per evaluation date uses a rolling union over the current dekad and the previous three dekads. A pixel counts as wet if it was mapped wet at least once within that four-dekad window. This choice limits omission error from cloud, haze, view geometry, and short-lived classification noise in optical surface-water products, while keeping commission error low when hydrologic states evolve on weekly to monthly scales. Short temporal compositing is widely used to stabilise water detection under intermittent obscuration and algorithm noise, and is suitable for large water bodies and floodplains observed by the Landsat and Sentinel series (Donchyts et al., 2016; Pekel et al., 2016). A one-month window is short relative to routing and storage in the Sudd and the Upper White Nile, yet long enough to bridge single contaminated scenes.

430 Lag definition follows the flood-wave tracking evidence for this basin from Sect. 2.5 and 3.2. Lags from zero to twenty four months are sufficient to capture responses from near-local wetting to the longest routed signals through the Sudd and upper White Nile, consistent with multi-month storage and travel times in this system (Nicholson, 2017a; Sutcliffe & Parks, 1999). At each lag, the four-dekad union is formed and wet pixels inside each sub-catchment mask are counted to give flooded area in square kilometres. Using Pearson correlation, the relationship between the Lake Victoria peak level at $t=0$ and sub-catchment wetland area at lag L is summarised as r^2 to emphasise variance. Visual diagnostics include r^2 as a function of lag and wet-
 435 area curves by hydrological year with period means and min-max shading for context and spread (Wilks, 2011).

The four-dekad union can retain short-lived floods that decay within weeks, which may slightly inflate wet area at some lags, although the one-month window bounds this effect and mitigates larger omission errors from single scenes. Using a fixed average month length introduces a day-scale offset at long lags, which is minor relative to dekadal resolution. Pearson correlation measures linear association and does not separate rainfall forcing from storage and routing, so estimated relationships reflect the combined influence of upstream storage in Lake Victoria and local hydro-meteorological processes (Nicholson, 2017a; Wilks, 2011).

445 2.7 Flood-Persistence Mapping to Track Sudd Wetland Activation

Flood persistence was assessed using the dekadal MODIS flood-extent series described in Sect. 2.1. For each month, we generated a four-dekad union by combining the file dated on the first of the month with the preceding three dekadal scenes. A pixel was considered wet if it was mapped wet in any of the four inputs. This short compositing window follows established surface-water mapping practice to stabilise detection under cloud and algorithm noise while retaining the signal of sustained inundation (Lin et al., 2019; Mueller et al., 2016; Pekel et al., 2016).

This monthly-union approach extends the method in Sect. 2.6 to a calendar-month scale, aligning with the 180-day SPI-6 framework that captures multi-month hydrological memory. The analysis was applied across the five South Sudan sub-



catchments to quantify persistence of inundation through successive months. These month-to-month persistence patterns were used to highlight zones exhibiting behaviour consistent with possible wetland activation or backwater influence.

3 Results

3.1 Evidence of a System-Wide Hydrological Anomaly (2019–2024)?

Between 2019 and 2024, the White Nile system experienced a sequence of multi-year basin-wide flood anomalies marked by sustained high water levels across both upstream lakes and downstream wetlands. Lake Victoria recorded peak water levels of 1136.48 masl in 2020, 1136.50 masl in 2021, and 1136.66 masl in 2024, all surpassing the historical maximum of 1136.42 masl observed in 1964. Concurrently, the Sudd Wetland reached its largest MODIS-derived extent of 163,475 km² in 2022. Notably, each year from 2019 to 2024 exceeded the prior maximum extent of 81,496 km² (2016), with annual maxima of 120,680; 111,684; 111,480; 163,475; 122,292; and 116,359 km² respectively. Fig. 2 illustrates these anomalies, with the period 2019–2024 highlighted in blue and 2022 marked explicitly as a light-green vertical strip.

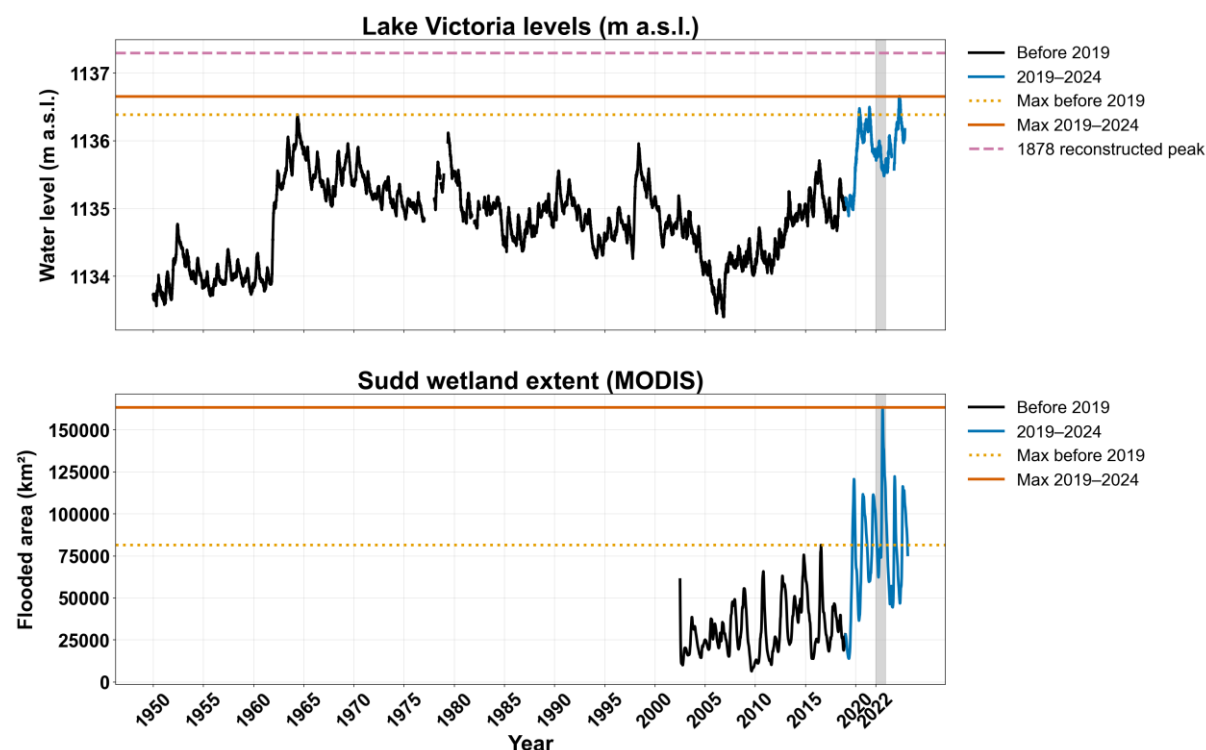


Fig. 2: Lake Victoria water levels (1950–2024) and Sudd Wetland extents (2002–2024), with the 2019–2024 anomalous period shown in dark blue and earlier observations in black. The orange dotted line marks the pre-2019 maximum, while the solid vermilion line denotes the highest peak observed during 2019–2024. The dashed magenta line represents the reconstructed 1878 Lake Victoria peak (1137.3 m a.s.l.) from Nicholson & Yin (2001). The shaded grey band highlights the 2022 flood year, when the Sudd reached its largest extent in the MODIS record.

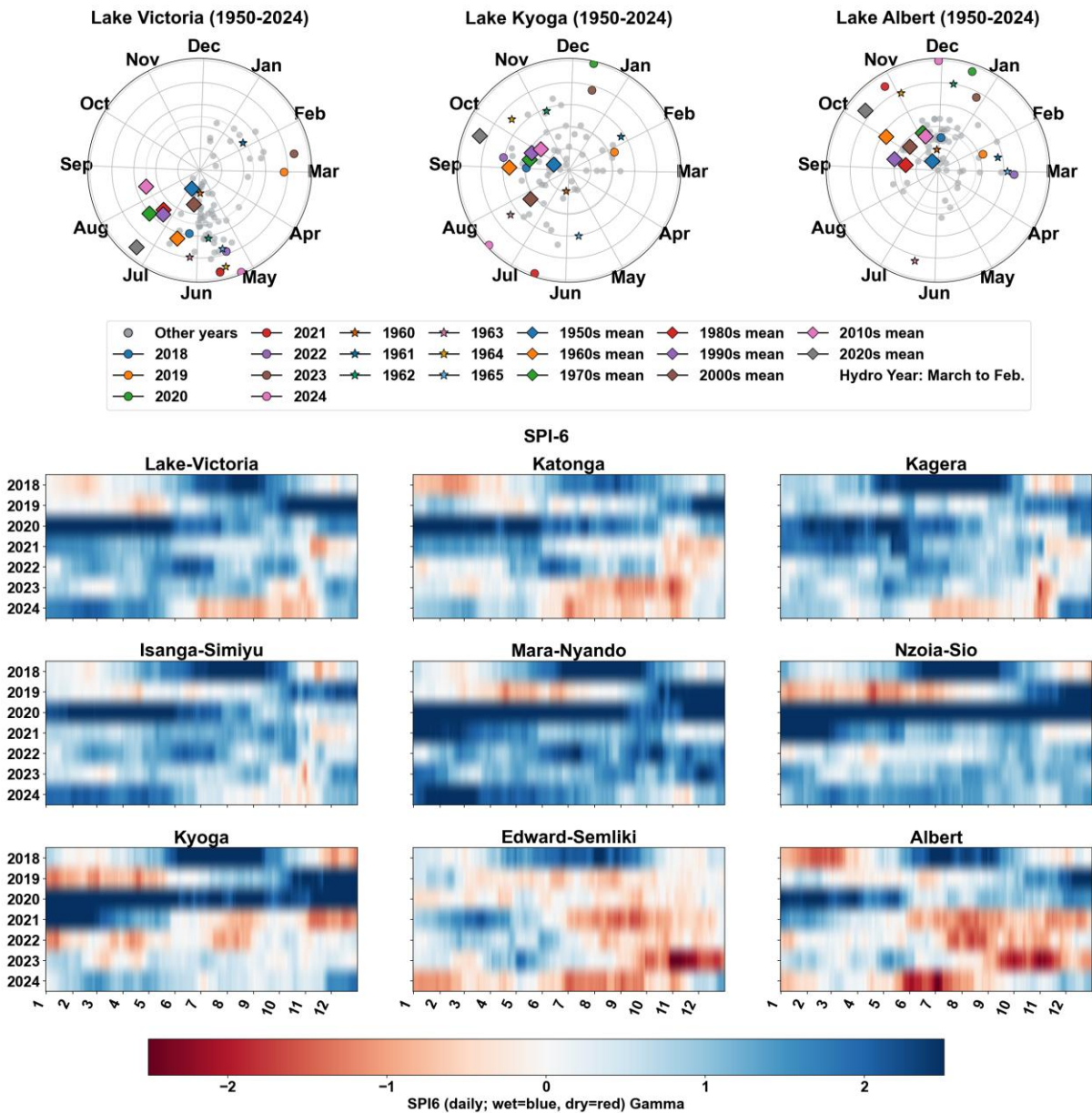


475 These concurrent upstream and downstream extremes confirm that both the headwaters (Lake Victoria) and terminal floodplain (Sudd Wetland) remained at record levels during overlapping intervals between 2019 and 2024. Rather than being confined to a single hydrological year, the anomalies persisted across multiple seasons, impacting all components of the lake-river-wetland complex system. This temporal persistence mirrors the duration of historical flood clusters, such as the 1961–1964 episode, and signals a sustained high-water regime rather than a series of discrete seasonal peaks.

480 **3.2 Rainfall and Lake Response**

3.2.1 Seasonal Rainfall Anomalies (SPI-6)

485 SPI-6 anomalies reveal a coherent, multi-season pluvial episode that began in late 2019 and persisted through 2020 and 2021 for some sub-catchments (Fig. 3 and 4). Positive rainfall anomalies developed near-simultaneously across most Upper White Nile sub-catchments, maintained above-normal conditions through successive seasons, and gradually weakened during 2021–2022 before becoming more spatially variable in 2023–2024. The timing and spatial extent coincide with the extreme positive Indian Ocean Dipole (IOD) of 2019, which amplified short-rains convection over East Africa (Ratna et al., 2021; Ummenhofer et al., 2009; Wainwright et al., 2021; Zhang & Han, 2021).



490 Fig. 3: Seasonality of annual maxima (top panels) and rainfall anomalies (bottom panels) for the main lake basins. The top panels
show the timing of annual maxima for Lakes Victoria, Kyoga, and Albert during 1950–2024, grouped by decade and referenced to
the hydrological year (March–February). The lower panels present six-month Standardized Precipitation Index (SPI-6) anomalies
for 2018–2024 relative to the 1983–2017 climatology. The palette (wet = blue, dry = red) follows standard SPI categories: severely
wet ($\text{SPI} \geq 2.0$), moderately wet ($1.0 \leq \text{SPI} < 2.0$), near-normal ($-1.0 < \text{SPI} < 1.0$), moderately dry ($-2.0 < \text{SPI} \leq -1.0$), and severely
495 dry ($\text{SPI} \leq -2.0$). Catchments contributing to each lake are grouped as follows: Katonga, Kagera, Isanga-Simiyu, Mara-Nyando,
and Nzoia-Sio drain into Lake Victoria; Kyoga drains into Lake Kyoga; and Edward-Semliki and Albert drain into Lake Albert.



The strongest and most persistent wet anomalies occurred in the Lake Victoria contributing catchments (Lake–Victoria, Kagera, Mara–Nyando, Nzoia–Sio, Katonga, Isanga–Simiyu), sustaining inflow and directly driving the exceptional rise and prolonged high levels in Lake Victoria and the downstream lake–river cascade (Fig. 3). Within the Kyoga basin, rainfall remained above average into early 2021, producing extended wet-season recharge that maintained high lake and wetland levels through 2022 before recession began in 2023. In contrast, the Albert basin exhibited only a moderate local wet anomaly, and its high levels arose primarily from inflow transmitted through the Victoria–Kyoga system rather than from local rainfall.

Downstream, the Sudd-feeding sub-catchments were more heterogeneous (Fig. 4): Baro Akobo Sobat and the eastern White Nile mirrored the 2019–2020 wet phase, whereas Bahr el Jebel and Bahr el Ghazal alternated between wet and neutral months, reflecting their transitional hydroclimatic setting between equatorial and Sudano–Sahelian regimes (Nicholson, 2017a; Sutcliffe & Parks, 1999).

These spatially extensive and persistent SPI-6 anomalies explain the sustained high lake levels and multi-year flooding observed during 2019–2022, underscoring the basin-wide reach of the 2019 IOD-driven rainfall anomaly.

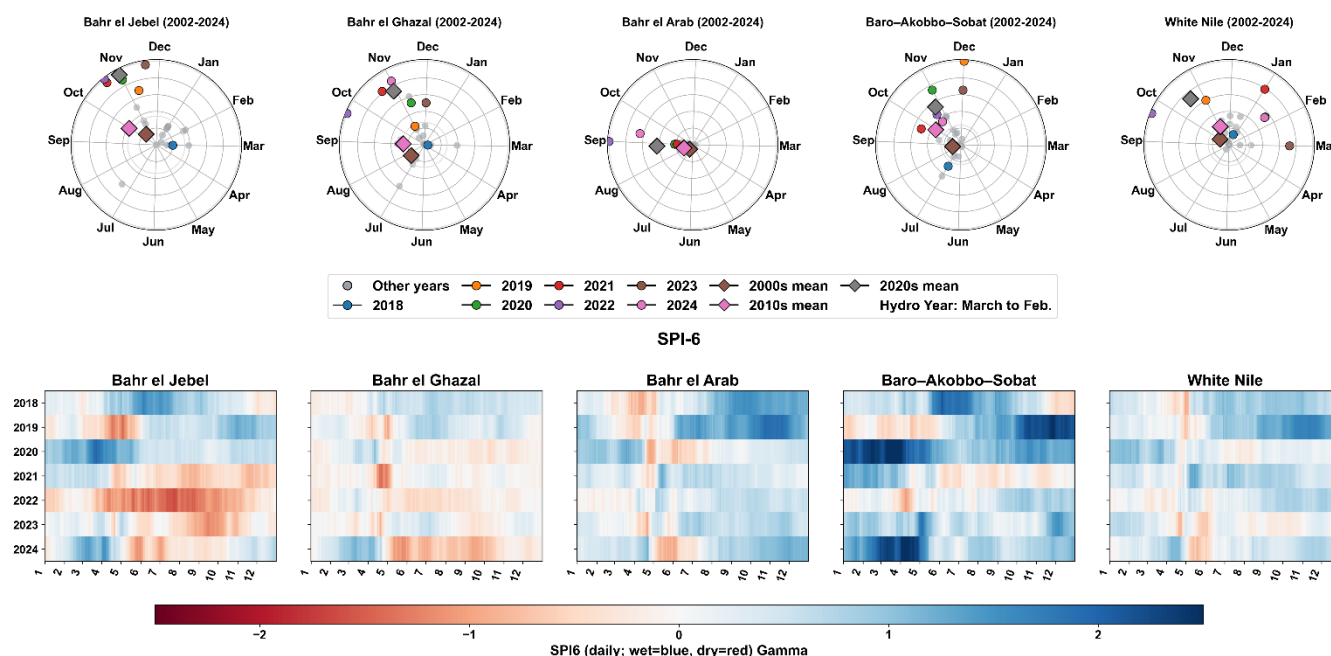


Fig. 4: Seasonality of annual maxima (top panels) and rainfall anomalies (bottom panels) for the South Sudan sub-catchments based on MODIS wetland extent and SPI-6 rainfall indices. The top panels show the timing of annual wetland-extent maxima for Bahr el Jebel, Bahr el Ghazal, Bahr el Arab, Baro Akobbo Sobat, and the White Nile during 2002–2024, grouped by decade and referenced to the hydrological year (March–February). The lower panels present six-month Standardized Precipitation Index (SPI-6) anomalies for 2018–2024 relative to the 1983–2017 climatology. The palette (wet = blue, dry = red) follows standard SPI categories: severely



520 wet ($SPI \geq 2.0$), moderately wet ($1.0 \leq SPI < 2.0$), near-normal ($-1.0 < SPI < 1.0$), moderately dry ($-2.0 < SPI \leq -1.0$), and severely dry ($SPI \leq -2.0$).

3.2.2 Annual Maxima and Inter-Lake Timing

Across 1950–2024, annual maxima followed a clear downstream progression, with Lake Victoria peaking on average on 10 May ($n = 75$), Lake Kyoga on 28 September ($n = 62$), and Lake Albert on 9 December ($n = 71$) (Fig. 3). This sequence reflects
 525 both latitudinal rainfall phasing and the cumulative storage which is a translation of flood waves along the Victoria-Kyoga-Albert cascade, where successive lakes and intervening wetlands progressively delay and damp seasonal peaks (Nicholson, 2017a; Sutcliffe & Parks, 1999). Decadal analysis shows that while the long-term means remained stable, inter-decadal variability was high. Lake Victoria's peaks were concentrated between mid-May and early June from the 1950s to the 2000s but shifted substantially earlier in the 2010s (mean 24 March). Kyoga's peaks generally clustered between September and
 530 December, except for unusually late behaviour in the 2000s (16 December) and earlier peaks in the 1980s (7 September). Lake Albert exhibited the widest spread, with peaks ranging from mid-October (1980s) to late January (1990s), before stabilising around December in the 2000s-2010s.

During the 2018–2024 high-water period, however, peak timing diverged sharply from the long-term pattern. In Lake Victoria,
 535 some maxima occurred much earlier than usual for some years, notably on 29 February 2019 and 18 February 2023, both preceding the historical mean by nearly three months. The intervening years of 2020 to 2022 maintained sustained high levels, with peaks clustering around mid-May and little sign of drawdown, indicating prolonged storage following the intense 2019–2021 rainfall anomalies (Wainwright et al., 2021) (Fig. 3).

540 Lake Kyoga displayed pronounced irregularity, with peaks spanning nearly the full hydrological year (February 2019 to July 2024) (Fig. 3). This disrupted sequence included very high stages in 2021 and 2022, when routing through the Kyoga wetland complex slowed markedly and floodplain inundation persisted across successive seasons. Such behaviour reflects the basin's strong buffering capacity and slow drainage response, consistent with observations of sustained wetland inundation and delayed outflow at Masindi Port to Lake Albert (Brown & Sutcliffe, 2013; Ma et al., 2024; NEMA, 2008).

545 Lake Albert followed suit, maintaining elevated base levels through 2021 and 2022 despite limited local rainfall input. Peaks in December 2020 and March 2022 (Fig. 3), both unusually high, confirm that the combined inflow from Victoria and Kyoga kept the system saturated for several consecutive years. This continuity underscores the long hydrological memory of the lake-river cascade and sets the stage for the downstream anomalies that followed in the Sudd.

550 Beyond Lake Albert, the flood signal propagated into the South Sudan sub-catchments, where exceptionally low relief and paleo-lake topography promoted broad wetland expansion and lateral connectivity. Bahr el Jebel, positioned immediately downstream of Albert, exhibited the earliest and strongest responses, with flood extents rising sharply in 2020–2022 in step



with sustained upstream inflow. Elevated stages along Bahr el Jebel raised the hydraulic base of the Sudd, facilitating spillover into adjacent zones such as Bahr el Ghazal and Bahr el Arab. Bahr el Ghazal showed delayed and dampened peaks, consistent with secondary activation through lateral inflow and backwater influence rather than direct channel transmission. Bahr el Arab displayed a more intermittent pattern dominated by local rainfall but experienced pronounced wetland activation in 2022 when exceptionally high Bahr el Jebel levels extended the inundation footprint north-westward. On the eastern side, Baro Akobo Sobat responded more to regional rainfall over the Ethiopian Highlands and to some extent to the spillover from Bahr el Jebel and the White Nile sub-catchments, showing compound influence rather than a purely upstream-driven flood wave. The White Nile corridor itself remained persistently wet during 2020–2022, its subdued hydrograph reflecting the integrated storage of the Sudd and the feedback of backwater effects from the downstream reach near Malakal. Together, these sub-catchment responses confirm that the 2019–2024 anomaly was not only a rainfall-driven event but a basin-wide hydrological reorganization in which the Sudd acted as a central storage node coupling the lakes and the floodplains.

Such multi-year persistence and spatial coherence have been reported in earlier wet phases linked to high inflows from the equatorial lakes (Mohamed et al., 2005b; Mohamed & Savenije, 2014; Nicholson, 2017a; Sutcliffe & Parks, 1999) and are consistent with recent evidence of sustained wetland connectivity and slow release following the 2019 positive IOD-driven rainfall (Hardy et al., 2023; Pietroiusti et al., 2024; Wainwright et al., 2021). The resulting disturbance in the timing and duration of lake and wetland peaks indicates that the 2019–2024 event was not only a rainfall anomaly but a system-wide shift in flood wave translation and storage behaviour. This evolving connectivity between lakes, wetlands, and downstream channels is explored next through segmental transit-time analysis across the Victoria-Kyoga-Albert-Sudd corridor.

3.3 Flood wave Propagation Through the White Nile System

Flood wave tracking between 2000 and 2024 revealed marked spatial and interannual variability in lag times from Lake Victoria to the Sudd Wetland (Fig. 5). Total system transit times ranged from 13.0 to 20.9 months, with a mean of 16.84 ± 1.95 months. Propagation was fastest during 2019–2021, coinciding with high upstream storage and sustained releases from Lake Victoria, while the 2022 hydrological year displayed the strongest delays, particularly across the low-gradient Albert-Sudd reach. These fluctuations highlight the crucial control exerted by intermediate storage and wetland attenuation within the White Nile corridor (Mohamed et al., 2005a; Mohamed & Savenije, 2014; Nicholson, 2017a; Sutcliffe & Parks, 1999).

Flood wave tracking-based analysis confirmed that the mean system transit time from Lake Victoria to South Sudan was 16.84 months, representing the physical propagation of the flood wave through the Victoria–Kyoga–Albert–Sudd cascade. Correlation patterns between lake levels and downstream wetland responses further support this connectivity but do not define transit time themselves. This finding overturns the long-standing assumption that flood translation from Lake Victoria to South



Sudan occurs within approximately five months, showing instead that the average system transit time is 16.84 months based on direct flood wave tracking observations.

To provide meteorological context, Fig. 5 and 6 overlay 180-day rolling rainfall totals aggregated over each contributing basin. This accumulation window mirrors the SPI-6 approach discussed earlier and captures the multi-month persistence of the 2019–2021 pluvial episode. The rainfall series confirm that the sharp system-wide wave in 2019 originated from the basin-wide positive IOD-forced rainfall anomaly, while the continued downstream translation into 2020–2022 reflected long hydrological memory and slow drainage rather than renewed rainfall input. In contrast, the Baro Akobo Sobat basin displayed an independent flood pulse during 2019, closely aligned with its local rainfall peak, confirming its rainfall-dominated flood response and only limited hydraulic coupling with the upstream lake system (Alfieri et al., 2024; Nicholson et al., 2021; Wainwright et al., 2021).

Across the main lake chain, Lake Victoria annual maxima generally occurred toward the end of the MAM long rains, often coinciding with or shortly following the month of highest rainfall over the Victoria basin. Lake Kyoga peaks followed with a visible lag, reflecting both local rainfall and inflow from Victoria, while Lake Albert peaks appeared after Kyoga, representing a mixture of local and upstream contributions. Within the Sudd, however, the rainfall season follows a distinct JJAS regime, and under a rainfall-dominated system the inundation peak would be expected to align with this period. Instead, observed Sudd maxima occurred later in the season, implying an additional contribution from the upstream flood pulse. This delayed timing reflects the influence of the Sudd’s low-relief paleo-lake surface, which supports broad storage, slow drainage, and sustained backwater effects. Other sources may also contribute, for example groundwater inputs, which were not examined in this study. The rainfall series are spatially aggregated over contributing areas, and the Sudd extent shown is an area-wide total; both choices limit attribution.

3.3.1 Segmental Transit Times (Victoria–Kyoga–Albert–Sudd)

610 i. Victoria–Kyoga segment

For the hydrological years 2000 to 2024, the Victoria–Kyoga segment, characterized by confined channel morphology, recorded a mean lag of 4.20 months and a standard deviation of 2.52 months with lags ranging from 0.3 to 11.1 months, highlighting substantial variability in this short reach. In 2018, the Victoria–Kyoga lag was 2.8 months, close to the long-term mean. It shortened further to 1.5 months in 2019, and reached its minimum of 1.5 and 1.2 months in 2020 and 2021 respectively, coinciding with sustained high levels in Lake Victoria. The segment remained fast in 2022 (1.2 months) and 2023, confirming the dominant role of high upstream storage in the transit times at this segment (Pietrojusti et al., 2024; Sutcliffe & Parks, 1999).



ii. **Kyoga–Albert segment**

This transitional zone, influenced by extensive wetlands and floodplain storage around Lake Kyoga, showed the more pronounced delays than the Victoria–Kyoga segment. From 2000 to 2024, lags ranged from 0.5 to 10.5 months, with a mean of 3.39 months and a standard deviation of 2.55 months. In 2018, the lag was 2.6 months, but it shortened sharply in 2019 to 1.5 months. By contrast, the segment slowed markedly in 2020 (4.8 months) and 2021 (4.2 months), despite fast upstream passage, reflecting the buffering role of wetlands around Lake Kyoga. It remained prolonged in 2022 (5.4 months) and 2023 (5.7 months), both above the long-term mean.

iii. **Albert–Sudd segment**

This long, low-gradient reach contributed the largest share of the overall system delay, reflecting the extensive floodplain and wetland storage that characterise the Sudd region. Between 2000 and 2024, transit times ranged from 6.8 to 12.5 months, with a mean of 9.25 months. In 2018, the lag was 11.4 months, close to the system average. It shortened sharply in 2019 to 7.2 months, the fastest since 2000, before lengthening to 9.8 and 10.3 months in 2020 and 2021. These longer lags indicate the onset of pronounced attenuation within the wetland complex, which culminated in the extreme flooding observed in 2022 as a downstream response to the 2021 Lake Victoria peak (Fig. 5). The longest lag in the 2018–2024 sequence occurred in 2022 hydrological year at 11.8 months, representing a delayed manifestation of the multi-year high-storage phase and the gradual reversal of attenuation processes as upstream lake levels began to decline in late 2022 into 2023. The 2022 inundation in the Sudd therefore reflected not a single-season rainfall anomaly but the compounded influence of sustained high inflows, prolonged wetland saturation, and backwater propagation through the White Nile corridor.

The Sudd extent used in the analysis in this section of the paper represents the combined flooded area across Bahr el Jebel, Bahr el Ghazal, Baro Akobo Sobat, Bahr el Arab, and the White Nile sub-catchments. While this aggregate captures the overall hydrological response of the lower basin, not all these sub-catchments are directly influenced by lake-fed flows. Baro Akobo Sobat and Bahr el Arab, for instance, respond mainly to local rainfall and tributary inflow, whereas Bahr el Jebel and Bahr el Ghazal are strongly affected by upstream discharges, wetland activation and backwater effects. These differences are examined further in Sect. 3.3.2, where the Sudd is disaggregated into its component sub-catchments to clarify spatial connectivity and coupling to upstream lakes.

iv. **Victoria–Sudd (White Nile)**

At the system scale, the Victoria–Sudd lag averaged 16.84 months over 2000–2024, ranging from 13.0 to 20.9 months with a standard deviation of 1.95 months. In 2018 it was 16.8 months, essentially equal to the mean of 16.84 months. Rapid downstream passage in 2019 shortened the lag to 15.4 months. In 2020 and 2021 the totals were below the mean, consistent with very short Victoria–Kyoga lags, but longer Kyoga–Albert transits (4.8 and 4.2 months) and longer Albert–Sudd transits (9.8 and 10.3 months) prevented the system from matching the 2019 minimum. The maximum occurred in 2022 at 18.4 months,

driven by slowdowns in Kyoga–Albert and Albert–Sudd, before shortening again in 2023 to 15.9 months due to a faster Albert–Sudd passage.

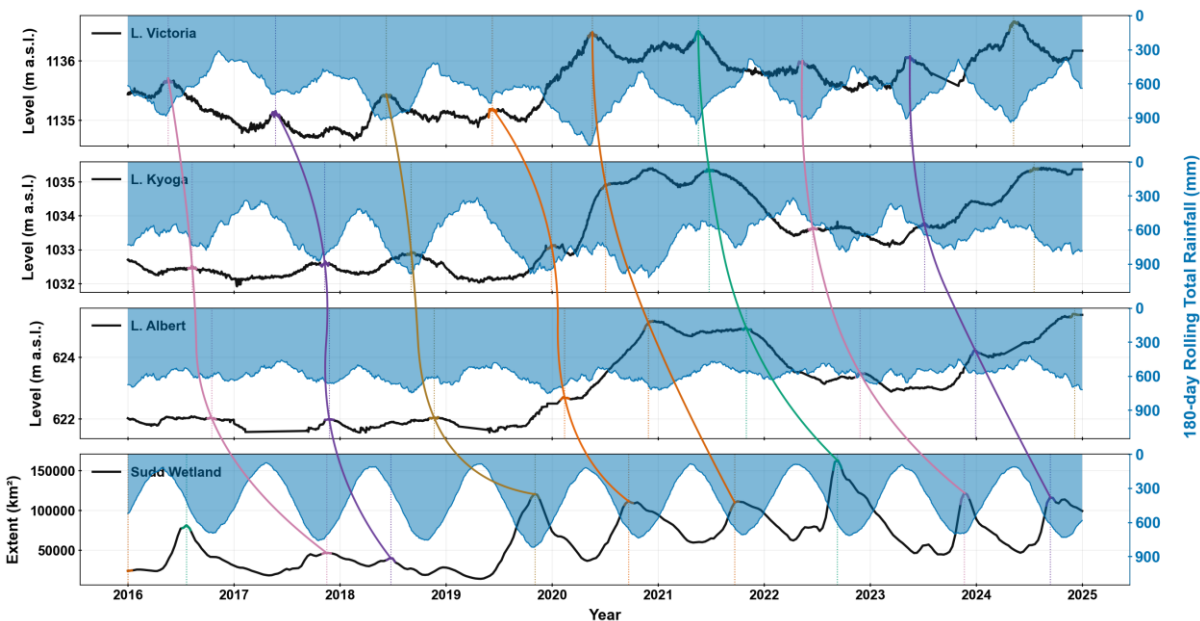


Fig. 5: Lake Victoria, Lake Kyoga, and Lake Albert water levels, and Sudd Wetland inundated extent, from 2016 to 2024. Coloured spline curves indicate annual flood-wave trajectories traced from the timing of Lake Victoria annual maxima through the downstream of the White Nile system. Blue shading on the secondary (right) axis shows 180-day rolling rainfall totals over each basin. The panel sequence (Victoria–Kyoga, Kyoga–Albert, Albert–Sudd) highlights the progressive translation of flood waves through the connected lake–river–wetland network.

3.3.2 Transit Time Variability at Sub-Catchment Scale in South Sudan

Flood wave transit times in the South Sudanese sub-catchments varied spatially with proximity to the White Nile main river, degree of hydraulic connectivity to upstream lakes, and tributary influence. Hydrological years 2018 to 2023 are considered, focusing on downstream progression of flood signals from Lakes Victoria, Kyoga, and Albert into five major sub-catchments: Bahr el Jebel (BeJ), Bahr el Ghazal (BeG), Baro Akobo Sobat (BAS), Bahr el Arab (BeA), and the White Nile (WN). Interpretation requires caution given the exceptionally flat paleo-lake topography in South Sudan. In the Sudd Wetland and surrounding zones, minimal elevation gradients allow extensive lateral flow and seasonal inundation that blur hydrological boundaries between adjacent catchments. The delineated sub-catchment borders should therefore be treated as indicative rather than hydrologically rigid. During high flows, water from Bahr el Jebel can spill laterally into Bahr el Ghazal and Bahr el Arab via braided channels; wetland expansion can also propagate from Bahr el Jebel into the White Nile corridor, even though the White Nile functions as the wetland outlet. On the eastern side, Baro Akobo Sobat can connect to both Bahr el Jebel and the



White Nile through seasonal overflow and wetland growth; between Baro Akobo Sobat and Bahr el Jebel the linkage is two way, with either sub-catchment able to spill into the other depending on which is more flooded. These dynamics justify inclusion of all five sub-catchments in the transit-time analysis, even where observed responses are not strictly downstream of Lake Victoria. Results should be read as indicative of regional flood coherence and wetland-scale connectivity, rather than direct channel routing alone within specific sub-catchments.

Bahr el Jebel (BeJ), positioned immediately downstream of Lake Albert, recorded an average flood wave transit time of 18.01 months from Lake Victoria between 2002 and 2023, with a standard deviation of 2.16 months and a range of 11.9 to 21.2 months. Transit times from Lake Albert to BeJ over the same period averaged 11.66 months, with a standard deviation of 2.39 months and a range of 4.8 to 14.6 months. Annual lags from Victoria to BeJ were 17.0 months in 2018, 16.9 in 2019, 17.1 in 2020, 17.2 in 2021, 18.3 in 2022, and 17.5 in 2023. Corresponding lags from Lake Albert were 11.6 months in 2018, 8.7 in 2019, 10.7 in 2020, 11.8 in 2021 and 2022, and 10.1 in 2023. The flood extent in BeJ closely followed hydrograph peaks of the upstream lakes, particularly Lake Albert, with sharp and sustained rises evident in 2020, 2021, and 2022 indicating strong hydraulic connectivity (Fig. 6).

Bahr el Ghazal (BeG) recorded a mean flood wave transit time of 17.01 months from Lake Victoria between 2002 and 2024, with a standard deviation of 1.25 months and a range of 13.0 to 19.3 months. From Lake Albert, the average lag was 10.65 months, with a standard deviation of 1.65 months and a range of 6.0 to 13.4 months. Year-specific lags from Lake Victoria were 16.6 months in 2018, 17.3 in 2019, 17.0 in 2020, 16.1 in 2021, 18.5 in 2022, and 17.5 in 2023. Corresponding lag times from Lake Albert were 11.1 months in 2018, 9.1 in 2019, 10.6 in 2020, 10.7 in 2021, 12.0 in 2022, and 10.1 in 2023. The BeG hydrograph showed a consistent lag behind Albert with visibly dampened peaks. During high BeJ stages, braided channels into BeG and partial backwater connectivity were activated. These conditions suggest delayed transmission, slowed by Bahr el Jebel flooding that activated braided connections into BeG, and by partial backwater influence within BeG rather than direct propagation from the upstream lakes (Fig. 6).

Baro Akobo Sobat (BAS) recorded a mean flood wave transit time of 16.32 months from Lake Victoria between 2002 and 2023, with a standard deviation of 1.56 months and a range of 13.0 to 18.5 months. From Lake Albert, the mean lag was 9.98 months (standard deviation 2.03 months; range 6.0 to 13.2 months). Year-specific lag times from Lake Victoria were 17.6 months in 2018, 16.7 in 2019, 16.1 in 2020, 17.4 in 2021, 18.5 in 2022, and 17.1 in 2023. From Lake Albert, lags were 12.2 months in 2018, 8.5 in 2019, 9.8 in 2020, 12.0 in 2021, 11.9 in 2022, and 9.8 in 2023. The 2019 flood extent in BAS showed a sharp and early rise that appeared disconnected from upstream trajectories, reinforcing the segment's local rainfall sensitivity and limited coupling to upstream lake-fed flows. Other sources may also contribute, for example groundwater inputs, which were not examined in this study (Fig. 6).



Bahr el Arab (BeA) recorded the shortest average transit time among the Sudd sub-catchments, with a mean lag of 15.60 months from Lake Victoria (standard deviation 1.35 months; range 14.3 to 19.7 months). The corresponding lag from Lake Albert averaged 9.26 months (standard deviation 1.50 months; range 6.8 to 12.6 months). Year-specific lag times from Lake Victoria were 14.7 months in 2018, 14.9 in 2019, 15.5 in 2020, 15.6 in 2021, 14.6 in 2022, and 15.7 in 2023. From Lake Albert, the lags were 9.2 months in 2018, 6.8 in 2019, 9.1 in 2020, 10.2 in 2021, 8.0 in 2022, and 8.3 in 2023. BeA showed isolated flood pulses with steep rises that aligned more with seasonal rainfall than with upstream wave propagation. Connectivity with Bahr el Jebel was intermittent. In 2022, partial alignment was evident and coincided with the very large extent in BeJ that followed multi-year high upstream lake levels; during this period, BeA showed wetland activation attributed to lateral spill from BeJ.

The White Nile (WN) sub-catchment recorded a mean transit time of 18.02 months from Lake Victoria between 2018 and 2024 (standard deviation 1.01 months; range 16.1 to 19.5 months), and 11.67 months from Lake Albert (standard deviation 1.30 months; range 9.3 to 14.6 months). Year-by-year lags from Lake Victoria were 16.7 months in 2018, 19.5 in 2019, 19.4 in 2020, 16.1 in 2021, 18.5 in 2022, and 19.5 in 2023. The corresponding lags from Lake Albert were 11.3 months in both 2018 and 2019, 13.0 in 2020, 10.7 in 2021, 11.9 in 2022, and 12.2 in 2023. Relative to other WN years, 2021 and 2022 showed notably larger extents, coincident with very large extents in Bahr el Jebel. During these periods, lateral spill from BeJ activated wetland areas within the WN corridor. The White Nile sub-catchment extent hydrograph demonstrated a stable, dampened and smoothed flood response consistent with its role as the integrated outlet of the upstream lake and wetland system.

Overall, the downstream delay sequence (Bahr el Jebel - Bahr el Ghazal - Bahr el Arab/White Nile) and the local rainfall signal in Baro Akobo Sobat emphasize that flood wave behaviour across the Sudd region reflects both longitudinal translation and lateral connectivity. The morphology of this former lake plain, coupled with extensive wetlands and distributary channels, supports spill, backwater, and seasonal re-activation processes that prolong flood residence and modulate peak timing (Hardy et al., 2023; Mohamed & Savenije, 2014). These spatial patterns and timings establish the foundation for the correlation analysis in Sect. 3.4, where we quantify how the Lake Victoria signal is expressed across the South Sudan sub-catchments.

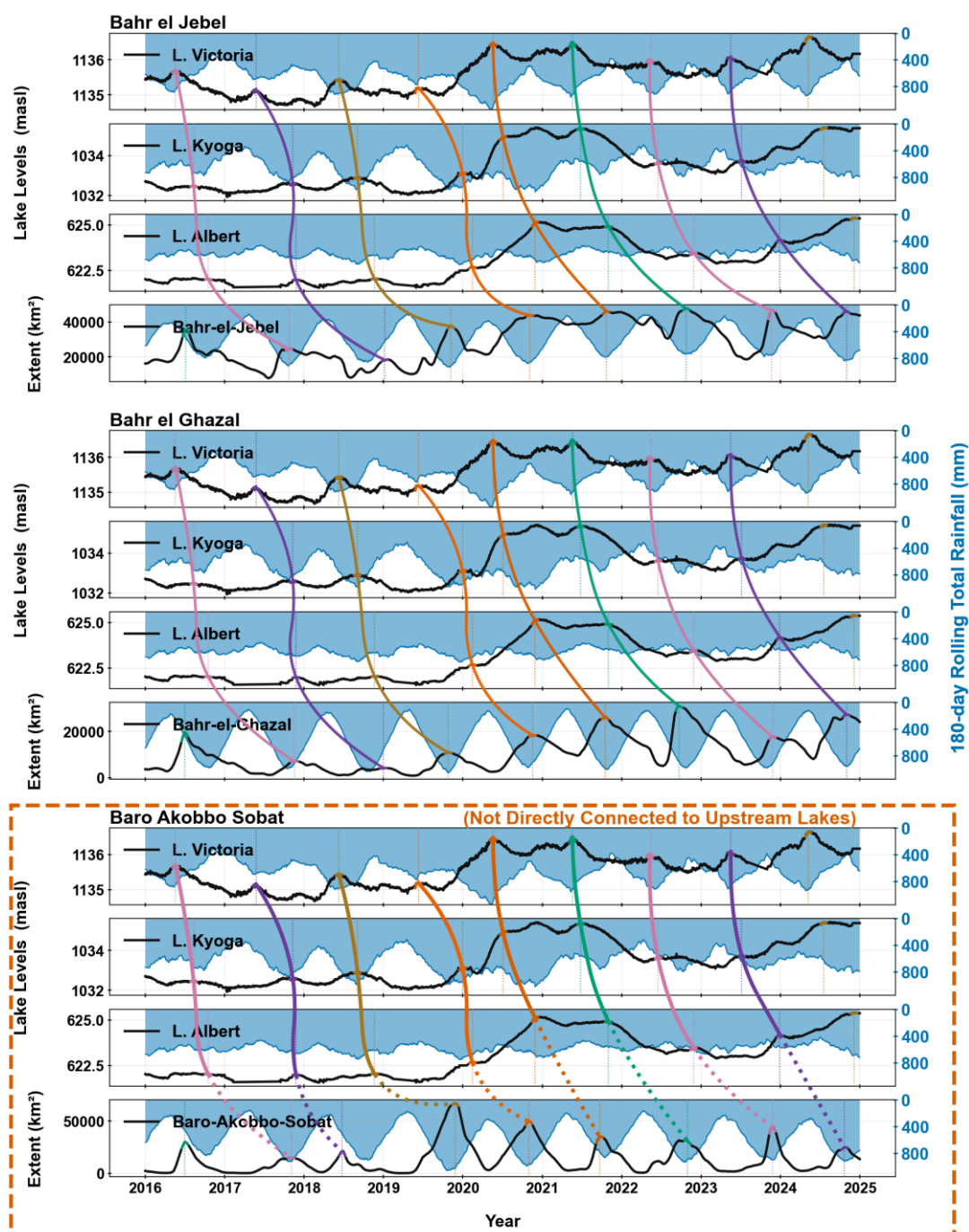


Fig. 6: Lake levels for Lake Victoria, Lake Kyoga, and Lake Albert, with dekadal wetland extent shown in the bottom panel of each subplot for the Sudd sub-catchments (Bahr el Jebel, Bahr el Ghazal, and Baro-Akobbo-Sobat) from 2016 to 2024. The top three panels are identical across subplots, while the bottom panel varies by sub-catchment. Coloured spline curves show annual flood-wave trajectories tracked from Lake Victoria through the lake-river-wetland system. The shaded blue areas on the secondary (right) axis represent 180-day rolling rainfall totals for each sub-catchment. The Baro-Akobbo-Sobat panel is outlined to highlight its limited direct hydraulic connection to the upstream lake chain.



740

3.4 Correlations Between Lake Victoria Peaks and Wetland Extent in the South Sudan Sub-catchments (Evidence of System Memory)

Across the White Nile system, correlations between annual Lake Victoria (LV) maxima and downstream wetland extents
 745 reveal a consistent lagged structure from the upper lakes to the Sudd (Fig. 7). These correlation lags reflect the timing of
 statistical coherence rather than physical flood wave translation and should therefore not be interpreted as actual transit times.
 Although correlation does not imply causation, the spatial and temporal patterns are physically consistent with (i) persistent
 LV releases, (ii) large intermediate storage within Lakes Kyoga and Albert, and (iii) stage-dependent backwater and spill
 interactions throughout the Sudd wetlands. Together these processes impart strong hydrological memory, meaning that current
 750 inundation states continue to reflect inflows from previous seasons or even previous years.

During the 2019–2023 high-storage period, correlation magnitudes increased sharply and peaks occurred predominantly during
 months of minimum wetland extent in the following hydrological year (roughly February–June). For a typical LV peak in mid-
 May, the corresponding correlation maxima at 9–13 months align with these dry-season minima, indicating that elevated
 755 upstream storage sustained base levels downstream long after the rainfall season. Such persistence is expected in a low-
 gradient, storage-dominated system where continuous but regulated LV outflow propagates slowly through Kyoga, Albert,
 and the Sudd. Consequently, the minimum extent becomes the clearest expression of the upstream signal, explaining why
 correlations are strongest then.

760 While correlation peaks outline the timing of maximum statistical association, they are supplementary to the physical flood
 wave tracking-based lags established in Sect. 3.3. The latter quantify actual flood wave propagation, whereas the former
 indicate the persistence of hydraulic linkage and memory.

Bahr el Jebel (BeJ)

765 The reach most directly connected to LV through the main Nile trunk shows the earliest and sharpest response. During 2019–
 2023, r^2 rose from 0.39 (at 0 months) to 0.93 (at 10 months) and 0.96 (at 11 months), compared with ≤ 0.45 before 2019. These
 9–12-month peaks (February–May next year) coincide with seasonal minima, confirming strong hydraulic linkage through
 Kyoga and Albert. Although these lags mark the timing of maximum statistical association, they represent correlation
 coherence rather than physical transit time. High BeJ stage also preconditions the Sudd by raising its baseline and promoting
 770 subsequent lateral storage and spill.



Bahr el Ghazal (BeG)

Pre-2019 correlations were weak (≤ 0.40). After 2019, r^2 exceeded 0.70 for months 10–13 lags and peaked at 0.80 (13 months). The delayed and weaker response indicates possible backwater and lateral spill from BeJ high stages rather than direct propagation. With BeG's very low gradients, elevated main-stem levels retard drainage and spread water across the distributary floodplains, producing high correlations during the next-year minima.

Bahr el Arab (BeA)

Pre-2019 correlations were moderate (approximately 0.4 at 4–6 months) but strengthened sharply post-2019, with r^2 ranging from 0.75 to 0.93 between 20–23 months. This almost 2-year lag potentially implies slow backwater transmission and prolonged storage within the Sudd corridor. Water first raises BeJ and Sudd stage, then progressively backs into the western floodplains and BeA channels, maintaining elevated extents long after the original LV peak.

Baro-Akobo-Sobat (BAS)

Dual peaks emerged post-2019 with r^2 approximately 0.55 at 14–15 months and 0.61 at 22 months. The 14–15-month peak corresponds to the JJAS rainfall season and local tributary response, while the 22-month band reflects remote influence from cumulative White Nile/Sudd storage. The coexistence of these peaks highlights the mixed local-and-remote regulation of the eastern Sudd sector.

White Nile (WN)

Below the Sudd, a dual behaviour appears. An early peak ($r^2 = 0.60$ at 1–3 months) reflects direct routing of LV contribution from the previous year through the lake chain. A later maximum ($r^2 = 0.72$ at 23 months) mirrors the delayed Sudd storage signal and backwater influence, demonstrating long-term transmission modes.

System-Wide Shift After 2019

Across all sub-catchments, correlation magnitudes and persistence increased markedly after 2019. Before 2019, r^2 rarely exceeded 0.4 and peaks occurred within 6 months. After 2019, r^2 of greater than 0.6 was common and peaks migrated to 9–13 months (BeJ, BeG) and approximately 22 months (BeA, BAS, WN). The transition signifies a high-storage, long-memory regime driven by sustained LV elevation and prolonged Sudd inundation.

Antecedent Wetland Minima as Predictors

The pronounced correlation during seasonal minima highlights the controlling role of antecedent wetland extent. Smaller minima indicate less residual storage and greater capacity for expansion in the upcoming rains, whereas large residuals imply

saturation and limited additional spread. Thus, the dry-season baseline conditions have become a reliable predictor of subsequent flood extent, reinforcing the system’s strong inter-seasonal memory.

Overall, while these correlations do not represent physical flood wave transit times, their spatial coherence and lag structure confirm persistent hydraulic connectivity, multi-season residence within the Sudd–White Nile corridor, and tributary modulation through backwater and spill effects.

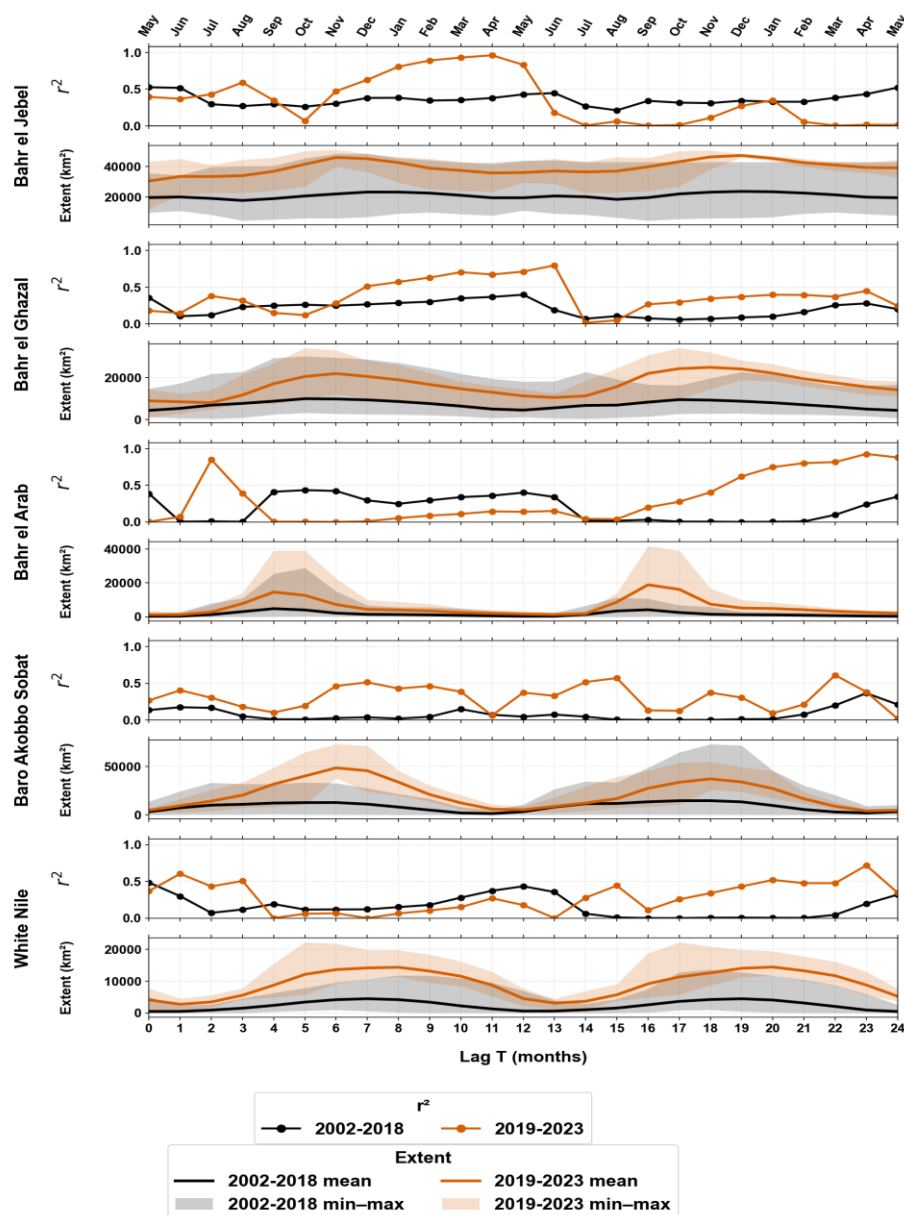




Fig. 7: Evolution of the relationship between Lake Victoria annual maxima at time T and wetland extent across South Sudan sub-catchments as a function of lag T(0–24 months). In each row, the upper panel shows the squared correlation (r^2) between the Lake Victoria peak level and downstream extent; the lower panel shows the corresponding extent variability (mean line and min–max envelope) for the pre-2019 period (2002–2018) and the post-2019 period (2019–2023). Month labels at the top align lags to a May reference month (T=0). Results highlight the progressive downstream delay and attenuation of the Victoria-origin flood signal from Bahr el Jebel to Bahr el Ghazal, Bahr el Arab, Baro Akobbo Sobat, and the White Nile.

3.5 Sudd Wetland Flood Persistence

Flood-persistence mapping captures the spatial evolution and duration of inundation across the Sudd and provides evidence of alternating rainfall- and inflow-driven activation (Fig. 8). The patterns show that wetland connectivity and flood longevity varied both seasonally and inter-annually, reflecting the joint influence of local rainfall, upstream inflow, and backwater effects.

In 2019, wetland expansion was concentrated in the eastern Sudd, particularly within the Baro-Akobo-Sobat (BAS) and White Nile (WN) sub-catchments. The two sub-catchments exhibited concurrent wetland expansion during July–October 2019, with flood parcels merging along their shared boundary. These are patterns consistent with two-way hydraulic interaction between BAS and WN. Later in 2019 and early 2020, the combined BAS-WN parcel receded eastward while Bahr el Jebel (BeJ) remained largely unconnected. This separation suggests that the 2019 activation was primarily rainfall-driven and locally sustained rather than propagated from the upstream lakes.

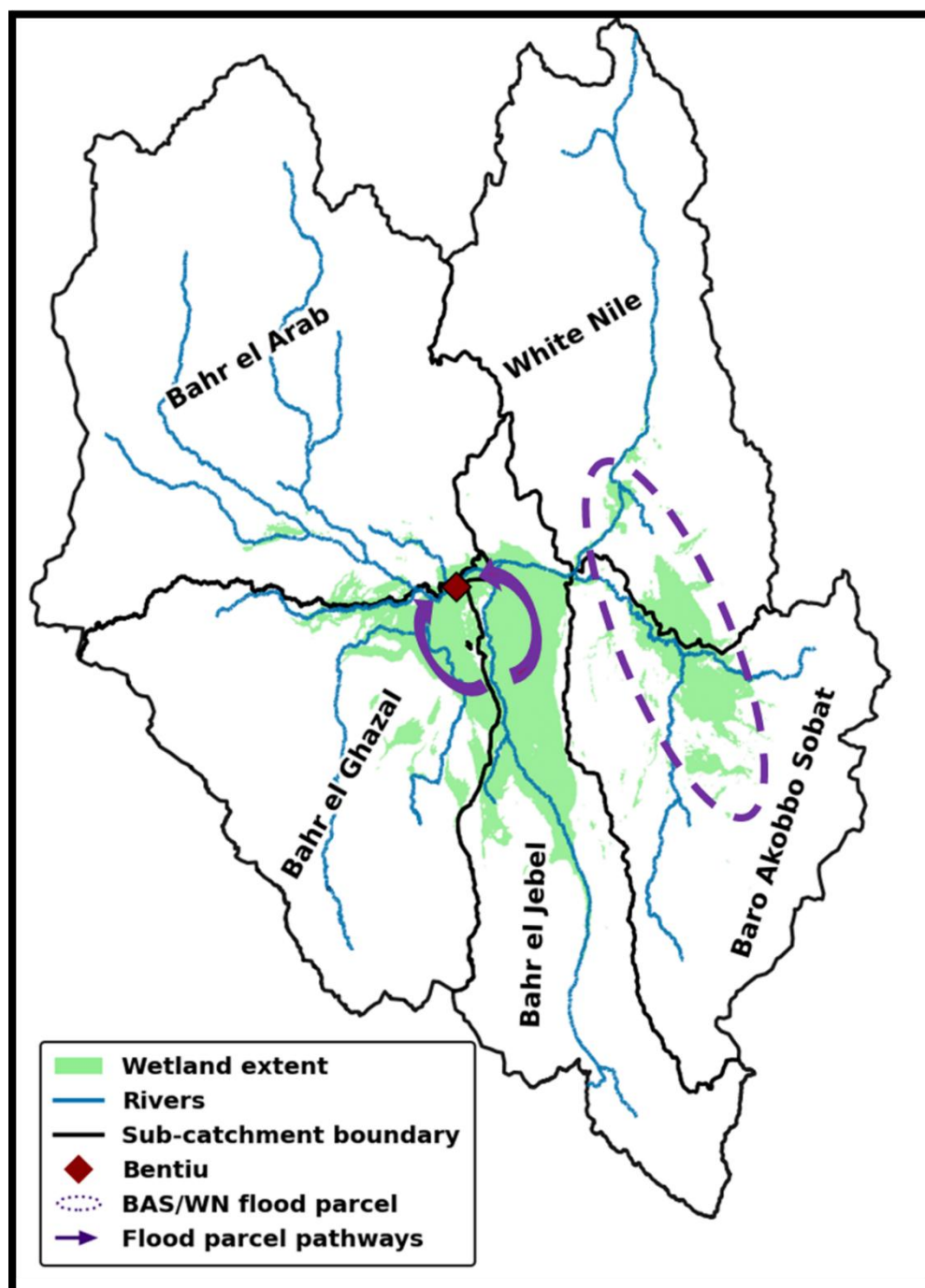
From May 2020 onward, wetland parcels from BeJ extended laterally westward to Bahr el Ghazal (BeG) and northwest toward Bahr el Arab (BeA). The westward arm through BeG connected with the Rivers Wau and Sue confluence. This arm extended northwards and converged with the other arm near Rubkona, forming a continuous flooded corridor through 2020 and this was the first instance of flooding in Bentiu during this period. During February–May 2021, peripheral areas slowly receded, but the core BeJ–BeG–BeA linkage remained intact, showing sustained storage and weak drainage despite limited rainfall input.

Late 2021 to early 2022 brought alternating pulses of expansion and contraction along the same corridor, followed by widespread flooding in August–September 2022. The latter event was most pronounced in BeA, consistent with intense local rainfall superimposed on high antecedent storage within the BeJ–BeG–BeA system. The combined influence of local rainfall and persistent upstream connectivity produced extreme inundation and the isolation of Bentiu during 2022.

Overall, the mapped sequences show a clear alternation between eastern (BAS–WN) activation in 2019–2020 and central-western (BeJ–BeG–BeA) activation in 2020–2022. These spatial and temporal patterns are consistent with wetland activation



845 and backwater effects: rainfall initially expands wetlands locally, while elevated BeJ and Sudd stages subsequently sustain or re-activate flooding through lateral and backwater pathways. Together they demonstrate the Sudd's long hydrological memory and the strong coupling between local rainfall and upstream inflow under prolonged high-lake conditions.



850 Fig. 8: Flood activation pathways and wetland connectivity across the South Sudan sub-catchments during the 2019–2024 high-water period. Green shading represents MODIS-derived wetland extent, blue lines show river networks, and black outlines mark sub-catchment boundaries. Dark purple arrows indicate the primary flood activation pathways from Bahr el Jebel into Bahr el



Ghazal and Bahr el Arab, while dashed purple ellipses highlight the Baro-Akobo-Sobat and White Nile (BAS/WN) flood parcel zones. The red diamond marks Bentiu, which remained inundated during the 2022 flood peak.

855

4 Discussion

4.1 How do flood waves propagate in the White Nile basin?

This study overturns the long-held assumption that flood translation from Lake Victoria to South Sudan occurs within five months. Flood wave tracking-based analysis establishes a mean system transit time of 16.84 months, confirming that the Victoria–Kyoga–Albert–Sudd corridor behaves as a slow-release, storage-dominated system rather than a rapid rainfall-runoff chain.

Flood wave propagation across the White Nile basin follows a spatially heterogeneous but hydrologically coherent pattern, influenced by the morphology of river channels, lakes and wetland connectivity. From Lake Victoria to Lake Kyoga, the Victoria Nile channel operates as a relatively confined fluvial corridor where the flood wave is rapidly transmitted during high-flow years, in contrast to the downstream reaches with wetland sections connected to the river leaving a wide river channel. This behaviour is consistent with open channel routing theory, where narrow channels with low storage propagate hydrograph peaks with minimal delay and attenuation (Beven, 2012; Chow et al., 1988). The persistence of short lags in this reach during dry years, including 2022, despite pronounced rainfall deficits (KMD, 2022; UNMA, 2022; WMO, 2023), underscores a system where flood wave celerity is governed by upstream hydraulic gradients and antecedent storage rather than local rainfall as the primary control in this short segment.

Downstream of Kyoga and especially below Albert, the system transitions from channel-dominated to storage-dominated flow. The Kyoga–Albert–Sudd system contains extensive swamps, floodplain pockets, and lake-like storage zones. Along the Albert Nile between Pakwach and the Uganda–South Sudan border, including the swamp-rich Obongi area, lateral connectivity during high flows promotes storage, diffusion, and delayed routing (Sutcliffe & Parks, 1999; Williams, 2018). Under high flow antecedent conditions, these landscape-driven attenuation effects can induce non-linear flood wave delays (Pappenberger et al., 2005). After Nimule, confinement through the Nimule–Juba corridor permits relatively fast local passage, then floodplain engagement increases sharply from Terekeka toward Bor and into the Sudd. Despite a broadly uniform low slope, the Albert–Sudd segment showed the longest and most variable travel times, which confirms that slope alone is a weak predictor of flood-wave velocity in this lake-wetland system. Internal storage, saturation thresholds, and wetland attenuation capacity dominate the response (Mertes, 1997). These dynamics affirm the necessity of explicitly modelling hydrological memory and nonlinear routing rather than assuming gradient-driven conveyance.

Rainfall diagnostics align with this routing picture. Annual-maxima circular plots and 180-day accumulations show JJAS peaks over South Sudan and over the Ethiopian Highlands, plus OND short-rains pulses that strongly affected the Lake Victoria



basin in 2019. Lake Victoria maxima in general respond to the MAM rains. Correlation analysis highlights coherent 9–13-month lags between Lake Victoria maxima and downstream wetland extent in Bahr el Jebel and Bahr el Ghazal, representing statistical alignment rather than physical travel time but consistent with the 16.84-month flood wave tracking-based mean
 890 propagation. These correlations indicate translation through Kyoga and Albert, then storage and backwater effects within the Sudd that preserve the lake signal into the next dry season, when the upstream control is clearest against low local rainfall.

A sub-catchment lens clarifies how flood energy is transmitted and redistributed. Immediately below Lake Albert, the Albert Nile conveys the lake-sourced pulse northwards through swamp-dominated sections in Obongi District, where local storage
 895 dampens the wave. Downstream, the river becomes confined again through the Nimule-Juba corridor, allowing faster passage before it enters a broad floodplain at Bahr el Jebel (BeJ). From there, the flood progressively engages wetland storage through Mongalla and into the Sudd, where channel-floodplain exchange becomes the dominant control on timing and persistence (Mohamed et al., 2005a, 2005b; Sutcliffe & Parks, 1999; Williams, 2018). Flood-persistence maps for July 2021 to October 2022 show a dominant arm from BeJ into the White Nile corridor that tracked via Fangak and the Lake No complex toward
 900 Rubkona, together with a second arm along the BeG–BeA fringe via Adok and Koch. The two arms connected near Rubkona and enclosed Bentiu for months before recession. This geometry and duration are consistent with an upstream lakes signal interacting with floodplain storage and backwater, not a short, through-going wave.

Responses in Bahr el Ghazal and Bahr el Arab illustrate intermittently connected fringe behaviour controlled by distributary
 905 links and partial backwater west of the main stem. Broad floodplains and shallow relief around Bentiu and Rubkona promote ponding and lateral exchange, which damps and delays peaks relative to BeJ and facilitates faster local clearance once lateral links close. The Baro Akobo Sobat system is the most rainfall-sensitive sector. JJAS inputs from the Ethiopian Highlands and the Sobat tributary produce early, sharp expansions that can be largely decoupled from lake peaks. Under exceptional stages, two-way connectivity can occur between BAS and BeJ across wetland expanses, so either sector can spill toward the other
 910 depending on which is more flooded, with significant transmission losses that prolong recession once storage is engaged (Mohamed et al., 2005b; Sutcliffe & Parks, 1999; Williams, 2018).

These behaviours together explain fast upstream transmission into BeJ, slow and variable propagation once floodplain storage engages, and long memory within the wetland complex that extends down the White Nile corridor. They also explain why
 915 correlation maxima often occur during the following year’s minima: antecedent wetland extent and residual storage set the baseline from which the next season expands.

Operationally, this has consequences. In the absence of national forecasts, global systems showed limited skill around Bentiu and the Sudd (Caldwell, 2022; Easton-Calabria, 2024). The wetland activation we document, including storage-driven
 920 attenuation, lateral spill, two-way coupling across the BeJ–BeG–BeA interface and the BAS confluence, and backwater effects,



disrupts simple rainfall-only or channel-only routing. This matches established Sudd hydrology and loss processes (Alfieri et al., 2024; Mohamed et al., 2005a; Rebelo et al., 2012; Sutcliffe & Parks, 1999) and points to the need for models that represent long lakes memory, floodplain exchange and backwater explicitly.

925 4.2 What dominated the 2019-2024 flooding sequence and its severity?

Evidence across timing, persistence, and spatial coherence indicates that rainfall-driven multi-year high levels in the upstream lakes, interacting with downstream wetland storage, were the dominant control on flooding between 2019 and 2024. Basin-scale concurrence is clear. Lake Victoria set new instrumented highs in 2020, 2021, and 2024, surpassing the 1964 maximum, while the Sudd reached its largest MODIS-era extent in 2022. The simultaneous inundation of lake shores and far-downstream
 930 plains demonstrates system-wide coherence from Victoria through Kyoga and Albert into the Sudd. The event was not a single shock but a multi-year cluster, in which above-average rainfall that persisted for consecutive seasons during 2019-2021 limited recession and recharged storage. Even when rains weakened during 2022–2023, delayed drainage and wetland retention maintained high levels (Caldwell, 2022). The lake and wetland storage transformed these multi-season anomalies into multi-year high lake levels persistence.

935 Rainfall anomalies and lake annual-maxima circular plots show that the exceptional 2019/20 positive Indian Ocean Dipole (IOD) produced intense OND rainfall over East Africa (Ratna et al., 2021; Wainwright et al., 2021). These above-average rains, that persisted over several consecutive rain seasons until 2021, initiated a sharp rise across Lakes Victoria, Kyoga, and Albert, and the Sudd, pushing the entire lake-wetland chain into a high-storage phase. Correlation analysis demonstrates a
 940 strong statistical coherence between this elevated state and downstream wetland response, reflecting persistent hydraulic connectivity rather than direct flood wave transmission. The observed 9–13-month correlation peaks indicate coherence with the upstream forcing but not the full physical transit time, which our flood wave tracking analysis quantifies at averagely 16.84 months between Lake Victoria and the Sudd. These correlations therefore complement, rather than replace, the flood wave tracking-derived transit times that describe the actual propagation through the lake-wetland system. They are strongest after
 945 2019, when the system entered a persistent high-lake phase, and confirm that hydrological memory, not renewed rainfall, was the principal control on downstream flooding.

Flood-persistence mapping reinforces this interpretation. In 2019–2020, activation began in the eastern Sudd (BAS–WN), consistent with intense JJAS rainfall over South Sudan and the Ethiopian Highlands. In 2020-2022, activation shifted westward
 950 to BeJ–BeG–BeA, coinciding with high lake stages and sustained inflow. The persistence and geometry of the connected BeJ–BeG–BeA parcel, which enclosed the Bentiu region for months, are physically consistent with wetland activation and backwater expansion from the main stem and limited recession due to high antecedent storage.



Historical analogues reveal the same compound behaviour. The 1878 flood, reconstructed at approximately 1137 masl for
 955 Lake Victoria, followed several wet years and produced extensive flooding along Bahr el Jebel and Lake Albert, with reports
 of large White Nile discharges and broad Sudd expansion near Mongalla (Gibb, 1984; Howell et al., 1988; Johnson, 1992;
 Nicholson & Yin, 2001).

Together, these patterns confirm a two-phase dynamic: initial rainfall-driven activation in the east followed by inflow- and
 960 storage-driven persistence in the central and western Sudd. The result was not a single flood pulse but a compound event
 sequence in which each wet season added to the existing storage base. This cumulative behaviour mirrors historical high-stand
 episodes (1878, 1916–1919, 1961–1964) where consecutive wet years generated prolonged flooding throughout the White
 Nile corridor (Gibb, 1984; Howell et al., 1988; Johnson, 1992; Nicholson & Yin, 2001; Sutcliffe & Parks, 1999). The 1916–
 1919 wet period likewise elevated Nile flows and refilled the lakes (Hurst & Phillips, 1938; Sutcliffe, 1974). The 1961–1964
 965 event, linked to a strong El Niño, raised Lake Victoria by about 2.5 m and again produced prolonged downstream flooding
 (Black et al., 2003; Gibb, 1984; Kite, 1982). Together, these lines of evidence confirm that the 2019–2024 sequence fits within
 the basin’s low-frequency, high-impact variability envelope, where hydrological memory translates climatic forcing into multi-
 season persistence (Hurst & Phillips, 1938; Nicholson & Yin, 2001; Sutcliffe & Parks, 1999).

By 2022, the Sudd reached its largest MODIS-era extent, representing a lagged response to multiple years of high inflow from
 970 the upstream lakes. This persistence illustrates the basin’s long hydrological memory. Once Lakes Victoria, Kyoga, and Albert
 entered their high-storage phase, downstream discharge and wetland levels remained elevated for several seasons even after
 rainfall weakened. During 2022–2023, when basin rainfall declined, stored water in the lake-wetland chain maintained
 extensive inundation and delayed recession. The exceptional August/September 2022 flooding in Bahr el Arab, likely
 975 intensified by local rainfall superimposed on the BeJ–BeG–BeA activated wetland system, exemplifies this compounding
 mechanism where antecedent storage, hydraulic coupling, and local input converge.

Hence, the severity of the 2019–2024 sequence reflects three interacting controls: (i) strong positive IOD forcing of rainfall in
 2019 that initiated basin-wide recharge; (ii) cumulative lake and wetland storage that sustained and expanded flooding through
 980 long-term attenuation; and (iii) localized rainfall reinforcement during later years that amplified already saturated conditions.

This interaction between climate variability and long-term hydrological memory was likely strengthened by background
 climate change. Indian Ocean warming is projected to increase the frequency and intensity of strong positive IOD events and
 to enhance short-rains over East Africa, while March–May long-rains trends remain mixed (Cai et al., 2014, 2018; Dunning et
 985 al., 2018; Endris et al., 2019; IPCC, 2021). Event-attribution studies place the 2019–2021 Lake Victoria rise within a multi-

decadal return period under the present climate but acknowledge a modest anthropogenic contribution to its likelihood and magnitude (Pietrojusti et al., 2024).

990 In short, climate variability provided the trigger, storage translated it into persistence, and emerging climate trends may increase recurrence probability. As wetland areas activated, attenuation increased, lateral spill spread water across floodplains, and backwater effects reinforced the high stand. By the time the flood wave reached the Sudd, the signal was governed less by short-term outlet variability and more by cumulative lake storage, rainfall anomalies, and floodplain exchange (Sene, 2000; Sutcliffe & Parks, 1999; Vanderkelen et al., 2018a).

995 4.3 Are these floods exceptional, or do they signal a hydrological shift?

While the magnitude and persistence of the 2019–2024 floods are striking, they are not without precedent. Nonetheless, the question remains whether this marks the beginning of a more permanent shift in hydrological functioning. The 16.84-month mean transit time identified here provides the clearest measure yet of how slowly flood energy moves through the basin, contextualising the 2019–2024 sequence within the system’s inherent long-memory behaviour. Current evidence is insufficient
 1000 to confirm a hydrological regime change; rather, it points to an exceptional cluster of events driven by a combination of climatic and hydrological factors. Given this uncertainty, it becomes essential to critically examine the underlying climatic anomalies, hydrological precursors, and system memory processes that may signal an emerging transition or alternatively, reaffirm the episodic nature of flood behaviour in the White Nile basin.

1005 One possible explanation is that this 2019–2024 period represents a rare recurrence within the basin’s natural long-term hydrological variability. Comparable flood episodes in the 1870s and 1960s also featured exceptionally high lake levels and multi-year persistence. Statistical analysis suggests that the 2019–2020 rise in Lake Victoria was approximately a 63-year event under current climate conditions (Pietrojusti et al., 2024). This means that floods of this magnitude are infrequent but not unprecedented and are expected only once in several decades. Paleoclimatic and documentary evidence from East Africa
 1010 supports the view that clustered extreme wet years have occurred in the past (Gibb, 1984). In this context, the 2019–2024 sequence is best viewed as a rare expression of the system’s intrinsic low-frequency, high-impact dynamics.

Another line of interpretation considers the antecedent state of the system. Prior to the onset of heavy rains in 2019, Lake Victoria had been recovering from a pronounced low stand experienced between 2000 and 2006. A combination of drought
 1015 and increased outflows following the Nalubaale dam expansion in 2000 drew the lake down to unusually low levels by 2005 (Kull, 2006). From 2007 onward, the lake level trended upward again, regaining storage. By the late 2010s the system was primed with a bit of additional capacity although still below the mid-1960s peak. When the heavy rains hit in 2019–2020, the initial dry ‘buffer’ may have been overcome relatively quickly, but the prior low conditions could have influenced management decisions or downstream impacts. The net effect of the prior low conditions and management decisions is complex, but one



1020 could hypothesize that the sharp rise was facilitated in part by the lake's post-2006 rebound and then amplified once that buffer
 filled. In summary, the sequence and severity of recent floods might reflect an interplay of natural climate variability with
 antecedent conditions set by the preceding dry period.

A third possibility, which carries more profound implications, is that the floods observed from 2019 to 2024 could represent
 1025 early indications of a shift toward a more flood-prone regime under a changing climate. Tropical river basins, particularly
 those with flat floodplain topography like the White Nile, are projected to have increasing frequency and intensity of flood
 events by the end of the 21st century under warming scenarios (Hirabayashi et al., 2013, 2021; IPCC, 2021). While attribution
 remains complex, several studies suggest that warming in the Indian Ocean, along with global climate change, is increasingly
 influencing rainfall extremes in East Africa (Black et al., 2003; Endris et al., 2019; Kolstad et al., 2021; Manatsa et al., 2012;
 1030 Manatsa & Behera, 2013; Roxy et al., 2011; Ummenhofer et al., 2009; Wenhaji Ndomeni et al., 2018). Notably, the extreme
 positive Indian Ocean Dipole (IOD) event of late 2019 played a significant role in generating unusually heavy rainfall across
 the region (Ratna et al., 2021; Wainwright et al., 2021). One study suggests that the lake-level rise was approximately 1.8
 times more likely to occur under present-day climatic conditions than under a pre-industrial baseline, with an estimated 7cm
 increase in magnitude attributable to anthropogenic warming but with broad confidence intervals (Ummenhofer et al., 2009).
 1035 This range of uncertainty necessitates caution in drawing definitive conclusions about systemic regime change. Nevertheless,
 these observations align with broader projections of increasing extreme rainfall events over East Africa under warming
 scenarios (Endris et al., 2019). In addition, recent analyses suggest a strengthening of the October–December short rains and a
 weakening of the March–May long rains across East Africa (Dunning et al., 2016, 2018; Nicholson, 2017b), potentially altering
 flood seasonality and compounding the risk of back-to-back high-flow years. Ongoing observations in coming years will be
 1040 critical to determine if water levels return towards the previous norm just like it was after past floods or if a new elevated
 baseline is established.

4.4 What else do we need to do next?

The findings highlight urgent needs across forecasting, modelling, and observation for lake-river-wetland systems like the
 1045 White Nile. Rainfall-only triggers are insufficient where flood dynamics are dominated by long-term storage and backwater
 effects. Predictive frameworks must explicitly account for lake levels, antecedent wetland extent, and hydraulic connectivity
 derived from correlation and persistence analyses. Without representing these slow components, forecasts will continue to
 misplace flood peaks and recessions.

1050 Existing global and regional flood forecasting and early warning systems show limited skill across wetland-dominated reaches
 such as the Sudd (Caldwell, 2022; Easton-Calabria, 2024). The long-memory behaviour documented here, including delayed
 correlations, multi-year persistence, and two-way connectivity, requires systems that integrate lake level monitoring,
 cumulative rainfall anomalies, and wetland extent into seasonal flood outlooks. Impact-based early warnings should assimilate



these storage and connectivity indicators, not only rainfall thresholds, and should be calibrated for the specific trackwave-
 based lags of approximately 16 months observed between upstream lake maxima and downstream wetland responses. The
 current configuration of regional early warning systems does not fully capture the long-memory behaviour of lake-river-
 wetland systems, leaving downstream populations at risk.

Hydrodynamic modelling should treat the Victoria–Kyoga–Albert–Sudd corridor as a single connected hydrologic unit from
 Jinja through Kyoga and Albert to Mongalla and the Sudd, with two-dimensional routing and explicit parameterisation of
 floodplain exchange, attenuation, and backwater effects. The mapped activation from BeJ toward Fangak, Lake No, and
 Rubkona, together with the parallel arm along the BeG–BeA fringe, indicates connectivity that 1-D routing or lumped models
 will under-resolve. Process-consistent bathymetry, floodplain roughness, and channel bifurcations are needed to simulate how
 storage propagates through the system (Mertes, 1997; Mohamed et al., 2005a, 2005b; Sutcliffe & Parks, 1999; Williams, 2018).
 Boundary conditions should couple lake water balances and outflows at Jinja where available, precipitation and evaporation
 over Lakes Kyoga and Albert, and tributary inflows at the Sobat confluence, while internal model physics must allow lateral
 spill between BeJ, BeG, and BeA and backwater effects along the White Nile corridor. Calibration and validation should use
 lake level and river gauge observations where available and supplemented with altimetry, and SAR-derived inundation for the
 reaches from Obongi and Nimule through Juba, Terekeka, Bor, Lake No, and Malakal, so that storage and exchange are
 constrained by observations rather than inferred indirectly (Pietroiuști et al., 2024; Sene, 2000; Vanderkelen et al., 2018a,
 2018b).

Observation gaps limit both this analysis and operational readiness. MODIS-based extents capture the footprint of inundation
 but not volume, and they struggle where emergent or floating vegetation masks open water, which can bias storage inference.
 Pairing the MODIS time series with C-band SAR from Sentinel-1 for open-water detection under vegetation, and with lake
 and river observations or altimetry data where available, would improve both extent and water level estimates, and allow
 volumetric change to be constrained more tightly (Rebelo et al., 2012; Ticehurst et al., 2014). Within our study, the lack of
 operator outflow records from Jinja prevented a direct quantitative partition of managed versus natural contributions. That
 constraint should be addressed through transparent data sharing on outlet rules and realised discharges, alongside consistent,
 cross-border gauge maintenance at key control sections such as Jinja, Pakwach, Mongalla, and Malakal (Sene, 2000; Sutcliffe
 & Parks, 1999).

Rainfall datasets also carry uncertainty. CHIRPS is widely used and performs well over much of East Africa, yet sparse gauge
 networks in South Sudan and northern Uganda reduce its calibration density, which can degrade local accuracy, especially for
 mesoscale convective systems. Future attribution and early-warning work should quantify this uncertainty and, where feasible,



blend satellite products with expanded rain-gauge networks to strengthen calibration in the Sudd and along the Albert Nile corridor (Funk et al., 2015).

Design standards and planning thresholds need to be revisited in view of non-stationarity. Teleconnections and projected shifts in seasonal rainfall over East Africa increase the chance of back-to-back wet seasons and shortened recession windows, which changes the effective return period of compound high-water years. Updating thresholds to reflect non-stationary risk, and making those thresholds impact-based, will better serve communities along BeJ, BeG, BeA, BAS, and the WN corridor (Endris et al., 2019; Hirabayashi et al., 2013, 2021; IPCC, 2021).

Methods used here carry important limits. Event alignment and correlation lags are referenced to sub-catchment specific baseline windows, so inferred timings and strengths are sensitive to the chosen pre-peak months, detrending choices, and any smoothing of anomalies. Transit time estimates from trackwave analyses summarise coherent propagation but do not prove causality, especially where two-way spill can occur between BAS and BeJ or where backwater reversals arise along the BeJ, BeG, and BeA interface. Flood-persistence maps quantify recurrence within monthly composites; they do not measure water depth or volume and may miss short-lived connections or open water masked by emergent or floating vegetation. Sub-catchment boundaries in the Sudd are indicative rather than hydraulically rigid, so mapped responses should be interpreted as zones of coherence and connectivity, not as fixed routing within strict borders. These synoptic choices are defensible for a basin-scale analysis, but they should be complemented by targeted observations and process-based, two-dimensional modelling to test specific hypotheses about storage, exchange, and backwater control.

Finally, Sustained monitoring within the Sudd is indispensable. Priorities include higher-resolution altimetry over lake and river tracks, routine flow gauging at wetland inlets and outlets, and classification of evolving flow pathways as vegetation and siltation modify channel geometry. Establishing groundwater observation networks along floodplain margins would clarify the role of subsurface storage in delaying recession. Integrating these observations into data-assimilative hydrodynamic frameworks would allow near-real-time estimation of storage and connectivity, improving both science and operational readiness.

5 Conclusion

Flood wave propagation in the White Nile is shaped less by hydraulic slope and more by storage, wetland attenuation, and antecedent state. The Victoria–Kyoga reach behaves as a comparatively confined corridor with short lags, whereas Kyoga–Albert and especially Albert–Sudd show longer, more variable transit due to floodplain exchange and lake-like sinks in Obongi. Local damping through the Obongi–Rhino Camp swamps, fast passage along the Nimule–Juba corridor, and progressive wetland engagement from Terekeka through Bor and Lake No illustrate how morphology and connectivity jointly determine flood wave behaviour. Flood wave tracking-based analysis shows that the mean system transit time from Lake Victoria to the



1120 Sudd is 16.84 months, overturning the long-held belief that flood translation occurs within only five months. These features underline the importance of hydrological memory and nonlinear routing in both interpretation and modelling.

The 2019–2024 floods were driven primarily by rainfall-forced multi-year high stands in the upstream lakes, compounded by wetland storage downstream. Correlation and persistence analyses confirm coherent statistical transmission of the lake signal
1125 through Kyoga and Albert into Bahr el Jebel and Bahr el Ghazal, with peak correlations occurring 9–13 months after Lake Victoria maxima. These patterns indicate sustained hydraulic connectivity and system memory but do not represent physical transit times. Flood-persistence mapping confirms these lags, revealing sequential activation: rainfall-driven expansion in the eastern Sudd (BAS–WN) in 2019–2020, followed by sustained inundation in the central and western Sudd (BeJ–BeG–BeA) during 2020–2022. The connected BeJ–BeG–BeA parcel that enclosed Bentiu for months exemplifies how antecedent storage,
1130 lateral spill, and backwater effects combined to sustain high levels long after direct rainfall ceased.

The sequence and severity of the 2019–2024 floods reflect a compound process: extreme rainfall associated with the 2019 positive Indian Ocean Dipole initiated the rise; consecutive wet seasons limited recession and recharged storage; and long system memory in the lake-wetland chain carried elevated levels into later years. Historical analogues in 1878, 1916–1919,
1135 and 1961–1964 show that such basin-wide high-water states recur under clusters of wet years, confirming that 2019–2024 represents a rare but plausible recurrence within the system’s natural variability envelope. The newly quantified 16.84-month average system memory provides a physical measure of this persistence and contextualises the 2019–2024 sequence within the long-term behaviour of the White Nile. However, projected increases in the frequency of strong positive IOD events and shifts in seasonal rainfall patterns may heighten the likelihood of back-to-back wet years and shorten recession windows in the
1140 future.

Action now should focus on forecasting, modelling, and observation at the system scale. Predictive frameworks must go beyond rainfall-only triggers to include lake levels, antecedent wetland extent, and hydraulic connectivity indicators derived from correlation and persistence analyses. Forecast calibration should account for the flood wave tracking-based lag of
1145 approximately 16 months between Lake Victoria peaks and downstream wetland response. Hydrodynamic models should represent the Victoria–Kyoga–Albert–Sudd corridor as a single continuous system with explicit floodplain exchange, attenuation, and backwater effects. Observational capacity must expand through integration of optical (MODIS) and radar (Sentinel-1 SAR) imagery, satellite altimetry, and strategically placed gauges to resolve volume, connectivity, and lag.

1150 Improving forecast skill will depend on shared data, co-designed hindcasts, and transparent evaluation between national hydrological services and model developers. Design standards and planning thresholds should be revised for non-stationary risk, acknowledging the likelihood of compound, multi-season high-water years in this long-memory system.



1155 **Code availability:** The analytical scripts used in this study are available in accordance with the INFLOW project data-sharing protocols. Access may be granted upon reasonable request to the corresponding author and subject to project data-governance agreements.

1160 **Data availability:** The data and code that support the findings of this study are available in accordance with the INFLOW project data-sharing protocols. Access may be granted upon reasonable request to the corresponding author and subject to project data-governance agreements.

1165 **Author contribution:** DM designed the research and carried out the analysis, interpretation, and discussion. HC, EB, and ES guided the research design and contributed extensively to the analysis, discussion, and interpretation. EN contributed to the flood persistence, wetland activation, and remote sensing components. CK and BZ contributed to the results interpretation. All co-authors contributed to the discussion and preparation of the manuscript.

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