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Climate Change Impacts on Flood Pulse Characteristics in the Barotse Floodplain, Zambia

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Key Points:

- Climate change will reduce flood magnitude and duration in the Barotse Floodplain, threatening thousands of flood-dependent livelihoods
- Coupled hydrological-hydraulic modeling shows areas lose annual inundation, exacerbating aridification and livelihood vulnerabilities
- Transhumance communities face greater food insecurity, limited health access, and reduced resilience as floods decline under climate change

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Abstract Tens of millions of livelihoods depend on floodplains, making them especially vulnerable to climate change. However, understanding how annual floods may change and impact local vulnerabilities remains limited. Daily precipitation and temperature projections were obtained from five CMIP6 (Coupled Model Intercomparison Project) General Circulation Models in the Inter-Sectoral Model Inter-Comparison Project (ISIMIP). These were input into a coupled hydrological-hydraulic model of the Barotse Floodplain, Zambia to obtain data on flood pulse timing, duration, and magnitude. Future decades (2030s, 2050s, 2070s) under three Shared Socio-Economic Pathways (SSPs 1–2.6, 3–7.0, 5–8.5) were compared with baseline data from the 1990s and 2000s to assess the impact of climate change. Climatic indices were also correlated with flood pulse characteristics to assess whether a driver of changes could be determined. Future floodwaves in the Barotse showed reduced durations and magnitudes, and altered timings of flood rise and recession compared to baseline periods. These differences were significant in the mid-to far-future. Large areas of the floodplain experience 1-to-2 month reductions in inundation duration, and some areas experienced no inundation in a hydrological year for the first time. The northern Barotse Floodplain, western escarpment, and Luena Valley exhibit the greatest sensitivity to future changes. The Barotse Floodplain will become increasingly arid under all climate scenarios, exacerbating existing challenges for transhumance communities dependent on floods, who face periodic food insecurity, malnutrition, and limited healthcare access. Intensified drought conditions under future climate change will undermine the resilience of local livelihoods, reflecting broader vulnerabilities faced by floodplain-dependent communities globally.

Plain Language Summary Tens of millions of people rely on floodplains for food, water, and other resources. However, climate change threatens these areas, and there is little understanding about how seasonal floods will change. To understand how future floods might change, rain and temperature data from five climate models were used to predict river flow and flood levels in the Barotse Floodplain. Data on when floods started, ended, their duration, and the size of floods were obtained. Future predictions (2030s, 2050s, 2070s) were compared with past projections (from the 1990s and 2000s) to assess how climate change has affected floods. Basic climate measurements were also explored to see if any changes could be explained. We show that future floods will be shorter, smaller, and occur at different times. By the 2050s and 2070s, these changes are significant. Some areas of the floodplain might experience no floods at all in the future, whilst others face shorter and less frequent flooding. The Barotse Floodplain will become drier in the future because of climate change, with changes likely worsening food insecurity, malnutrition, and health access which are already major issues in the region.

1. Introduction

Climate change is expected to alter global hydrological cycles with significant implications for hydrological extremes (Allan et al., 2020; Gu et al., 2022; Gudmundsson et al., 2021; Tabari, 2020). Africa is considered to be particularly vulnerable due to projected increases in precipitation variability that will amplify the existing sensitivity to floods and droughts (Doumbia et al., 2014; Hamududu & Ngoma, 2020). There is limited understanding of the precise direction and magnitude of changes to Africa's hydrological extremes. This is due to its hydrology being influenced by natural climate variability, such as the Inter-Tropical Convergence Zone (ITCZ), Indian Ocean Dipole, and El Niño Southern Oscillation (ENSO). These drivers operate on intra-annual to decadal

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timescales, which are driven by complex atmosphere-land-ocean interactions (Conway, 2002; Conway et al., 2009; Papa et al., 2023). Their combined influence modulates distinct seasonal rainfall regimes, with small variations in individual drivers and compounding interactions between them leading to significant droughts and flooding. Southern Africa is particularly sensitive to extreme hydrological events occurring in response to spatio-temporal variability in the distribution of precipitation (Gaughan & Waylen, 2012; IPCC, 2022; Karypidou et al., 2022; World Food Programme (WFP), 2021) and changes in precipitation have already been observed in the last few decades, albeit with uncertainty (Alahacoon et al., 2022; Gaughan & Waylen, 2012; Libanda et al., 2020; Makondo & Thomas, 2020; Zeng et al., 2019). Understanding the potential impacts of these changes is crucial as sub-Saharan Africa is the location of globally important river basins, such as the Zambezi which support millions of livelihoods through its floodplains.

The Zambezi catchment spans across eight countries and covers 1.37 million km^2 of land (Beck & Bernauer, 2011). It is the African basin most threatened by climate change impacts (Beilfuss, 2012; Fant et al., 2015; IPCC, 2001) due to its low runoff efficiency, low drainage density, and high aridity (Beck & Bernauer, 2011; Beilfuss, 2012; Emerton, 2003; Fanshawe, 2010; MacDonald, 2007; Ndhlovu & Woyessa, 2021; Winsemius et al., 2006). The climate of the Zambezi is highly variable and associated with significant climatic phenomena, the most important of which are the ITCZ and the ENSO (Farnsworth et al., 2011; Gannon et al., 2014; Hachigonta et al., 2008; Jury et al., 2002; Libanda et al., 2020; Libanda & Ngonga, 2018; Richard et al., 2001). Increased rainfall is generally expected in La Niña years and decreased rainfall in El Niño years (Lenssen et al., 2020), and the ITCZ controls spatial and temporal variability of precipitation (Lowman et al., 2018; Zeng et al., 2019). Climatic extremes have been recently associated with ENSO, such as the 2015/2016 high-intensity drought linked to El Niño (Libanda et al., 2024), and the recent 2023/2024 drought across swathes of Southern Africa. The ITCZ is expected to shift toward the equator, widen, and weaken under future warming (Zhou et al., 2020). However, there is limited consensus surrounding how the ITCZ and ENSO will change. For example, the IPCC Sixth Assessment Report only indicated "medium agreement" on the projected ITCZ changes (IPCC et al., 2021). Evidently, there is uncertainty surrounding how discharge in the Zambezi will be altered due to the complexity of the Southern Africa climate processes and their interactions (Fant et al., 2015; Ndhlovu & Woyessa, 2021). The climate system is non-linear (Quagraine et al., 2019), as is the Zambezi's relationship between discharge and precipitation, hence minor changes in precipitation could have a substantial impact on annual discharge (Beilfuss, 2012).

Whilst numerous studies have attempted to model climate change impacts on the Zambezi's discharge (Chomba et al., 2022; Hughes & Farinosi, 2020; Kling et al., 2014; Liechti, Matos, Boillat, Portela, & Schleiss, 2014; Liechti, Matos, Segura, Boillat, & Schleiss, 2014; Spalding-Fecher et al., 2016; Stanzel & Kling, 2014; Yamba et al., 2011), very few (e.g., Chomba et al., 2021) have considered the subsequent implications to the surrounding floodplains. Large African floodplains (>1,000 km^2)—such as the Barotse floodplain, the Okavango Delta, the Sudd wetlands, and the Chobe wetlands—experience at least one seasonal flood pulse per hydrological year, lasting for weeks or months in response to strong seasonal variations in discharge (Charlton, 2008; Gaudet, 1992; Marchand, 1987; Welcomme, 1975), and are an ecologically, hydrologically, and anthropologically significant ecosystem. The global importance of large African floodplains originates from the substantial ecosystems services they provide, of which millions of livelihoods are locally dependent upon for food, water, and building resources (Cai et al., 2017; International Union for Conservation of Nature (IUCN), 2003; Junk et al., 1989; Laborde et al., 2018; Marchand, 1987; Moritz et al., 2016; Petsch et al., 2023; Rebelo et al., 2010; Schuijt, 2002; Schuijt, 2005; Thompson & Polet, 2000).

While more research exists for floodplains in Asia (Arias et al., 2012; Chen et al., 2021; Orieschnig et al., 2022; Try et al., 2020; Västilä et al., 2010), South America (César Fassoni-Andrade et al., 2023; Ivory et al., 2019; Ronchail et al., 2018) and Australia (Colloff & Baldwin, 2010; Jardine et al., 2015), these studies tend to focus on specific ecological or fisheries consequences (Jardine et al., 2015; Junk, 2013; Kelkar et al., 2022; Murray-Hudson et al., 2006; Wei & Zhou, 2023) with limited analysis of overall flood pulse variables. Yet, flood dynamics are of great importance to local floodplain livelihoods in regions of Asia, South America, and Australia, as well as Africa and globally (Chimweta et al., 2022; Dikgola, 2015; Martínez-Capel et al., 2017; Schneider et al., 2011; Sidibé et al., 2016; Thito et al., 2016). Changes are observed to be occurring (Colloff et al., 2016; Katz et al., 2020; Orieschnig et al., 2022; Sandi et al., 2020; Silio-Calzada et al., 2017; Singha et al., 2020; Szabo et al., 2016) with studies globally documenting communities reporting negative impacts to their livelihoods due to flood pulse changes (Almudi & Sinclair, 2022; Coomes et al., 2016; Leauthaud et al., 2013; Oviedo et al., 2016).

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Despite the importance of floods, there is a common tendency to define floods as "disasters" without reference to what constitutes an abnormal flood (Denevan, 1996; Li et al., 2016; Lima et al., 2015; Marengo & Espinoza, 2016; Pinho et al., 2015; Sherman et al., 2016). Flood impacts are highly variable in both positive and negative dimensions (Bayley, 1991; Coomes et al., 2016; Langill & Abizaid, 2020; List & Coomes, 2017; Niman et al., 2024; Sajid & Bevis, 2021; Sherman et al., 2015), and the routine classification of "bad floods" ignores the reality of floodplain dwellers having livelihoods closely linked to normal flood cycles (Egedorf, 2018; Langill & Abizaid, 2020; Pinho et al., 2012; Sherman et al., 2015). Additionally, it simplifies floods and fails to understand the dimensions of which floods are considered extreme, such as timing or magnitude (Langill & Abizaid, 2020). Floods are highly variable depending upon local social context and geographic factors (Islam et al., 2013), so must be considered explicitly in their local occurrence.

Local communities have adapted to the predictable interannual variability in annual floods in order to mitigate and even enhance the floods impacts on their activities such as agriculture (Mapedza et al., 2022; Nguyen & James, 2013; Singh et al., 2021) and access to healthcare services (e.g., Mroz et al., 2023). However, these adaptations are based on indigenous knowledge that links the normal flood characteristics (amplitude, duration, and timing) to local livelihoods. Due to climate change, flood characteristics are becoming more erratic, with unpredictable shifts in timing, magnitude, and duration. The erratic variability is potentially beyond what has been observed by these communities historically, which disrupts their established adaptation strategies (Beilfuss, 2012; Cai et al., 2017; Try et al., 2020). Consequently, floodplain communities are increasingly vulnerable to future endogenous and exogeneous shocks, as any abnormal variation to seasonal flood characteristics under climate change will affect the strong interrelationship that exists between floodplain communities and their floodplains (Moritz et al., 2016). However, there has been a lack of research on how projected climatic changes will impact amplitude, duration, and timing characteristics of flood pulses.

The Barotse Floodplain is an example of such a threatened ecosystem with dependent communities. While there is a general understanding of its flood pulse characteristics regarding when flood rise, recession, and peak occurs (timing, duration) in addition to peak extents and overall magnitude (amplitude) (Cai et al., 2017; Willis et al., 2022; Zimba et al., 2018), no assessment has yet been made of the future impacts of climate change on these characteristics. There remains a significant gap in the literature concerning climate change impacts on flood pulse variables, particularly in African floodplains where there is a demand for understanding (Alexander et al., 2018; Chomba et al., 2021; Ficchì & Stephens, 2019; Hiernaux et al., 2021; Ogilvie et al., 2015).

Future population growth will intersect with the impacts of climate change, amplifying flood hazards on global floodplains and increasing the need to understand flood pulse variables in order to inform effective mitigation and adaptation strategies (Yamazaki et al., 2018; Zischg & Bermúdez, 2020). Given that flood pulses sustain livelihoods worldwide, it is critical to understand these potential changes; yet no comparative framework to study dynamics alone exists. The aim of this study is to present a novel methodology assessing climate change impacts on flood pulse characteristics on the Barotse floodplain. We input open-access global climate model outputs into a coupled hydrological-hydrodynamic model to assess the impacts of climate change on flood pulse characteristics. We first characterize the flood pulse system of the Barotse Floodplain before determining the impact of climate change on the timing, duration, shape, and magnitude of the Barotse Floodplain floodwave. We identify the most susceptible regions to climate change impacts on two important metrics: flood inundation duration and decadal flood frequency. Finally, we elucidate specific climate drivers hypothesized to drive changes in flood pulse characteristics.

2. Methods

2.1. Study Area

The Barotse Floodplain is located within the Upper Zambezi valley, Zambia (Figure 1). The hydrology of the floodplain is dependent on multiple tributary inflows, complicating its storage-inflow relationship (Makungu, 2019). These inflows originate from the five upper sub-catchments of the Upper Zambezi valley: Luena, Kabompo, Luanginga, Lugwebungu, and the Upper Zambezi (disambiguation: a distinct sub-catchment sharing the nomenclature of the wider basin). The spatio-temporal variation of water exchange processes between the Zambezi and these tributaries is inadequately characterized (Makungu, 2019).

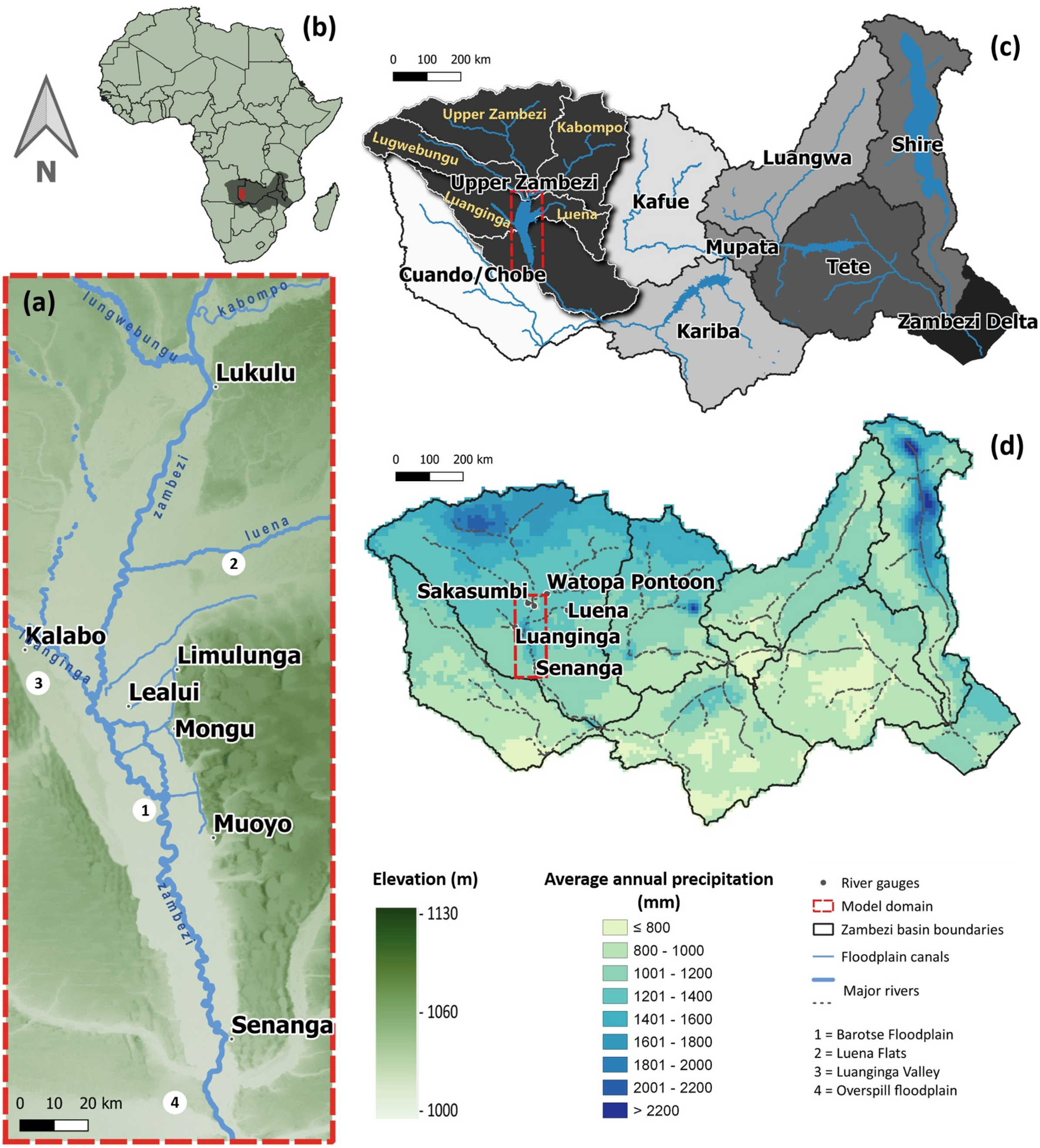

Figure 1. (a) Map of the Barotse Floodplain and associated wetlands, major waterbodies, and key settlements. (b) Map of the continent on Africa, with the gray shaded regions highlighting the Zambezi basin and the red shaded region highlighting the model domain. (c) The nine major sub-catchments of the Zambezi basin and major waterbodies; the Upper Zambezi sub-catchment is further discretized to show the five catchments modeled in the coupled hydrological-hydrodynamic process. (d) Decadal average of annual precipitation in the 2010s, based on NASA's integrated Multi-satellitE Retrievals for GPM (Huffman et al., 2014); key river gauges used in the modeling process are displayed.

Average annual evapotranspiration is ~1,560 mm and average annual precipitation is ~830 mm on the floodplain; however, floodplain inundation is predominantly driven by precipitation in the upper sub-catchments where the average annual precipitation is ~1,400 mm (Beilfuss, 2012; Cai et al., 2017; Chikozho & Mapedza, 2017) (Figure 1). The Zambezi river experiences a strongly seasonal discharge due to the high inter-annual variation in precipitation caused by the movements of the Intertropical Convergence Zone (ITCZ) (Beilfuss, 2012; Hardy et al., 2019). This seasonality subsequently influences inundation of the Barotse Floodplain. The majority of rainfall occurs in December, January, and February (DJF), resulting in floodwaters rising from December onwards. However, there is a delay of approximately 2 months between peak rainfall and peak inundation in the Barotse (Cai et al., 2017), so peak inundation typically occurs in either late March or early April. Peak Barotse inundation extent can be as great as 10,750 km^2 (Zimba et al., 2018), with extensive, deep, and slow-moving floodwaters persisting for several months due to the floodplain being extremely flat and attenuating flow (Beilfuss, 2012). Flood recession typically occurs in June or July.

2.2. Climate Forcing Data

Historical and future climate data were obtained from phase 3b of the Inter-Sectoral Model Intercomparison Project (ISIMIP 3b) (Lange & Büchner, 2021). ISIMIP provides a consistent framework for attribution of climate change impacts, and its 3b protocol provides bias-corrected and statistically downscaled (to 0.5° × 0.5° spatial resolution) climate forcing data from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) (Cucchi et al., 2020; Eyring et al., 2016; Lange, 2019; Lange et al., 2021). Daily projections of total precipitation (kg m^{-2} s^{-1}) and near-surface air temperature (K) were used from five General Circulation Models (GCMs) (IPSL-CM6A-LR, GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, MRI-ESM2-0) for three Shared Socioeconomic Pathways (SSP) (1–2.6, 3–7.0, 5–8.5). The five GCMs included in the protocol are considered representative of the entire CMIP6 ensemble due to the variation in climate sensitivities of the different models, as well as their structural independence and variation in process representation (Bonnet et al., 2021; Dunne et al., 2020; Jägermeyr et al., 2021; Lange & Büchner, 2021; Mauritsen et al., 2019; Müller et al., 2018; Sellar et al., 2019; Yukimoto et al., 2019). ISIMIP outputs are thus suitable for climate change impact studies, and the outputs have been used in a variety of studies interested in changes in hydrology (e.g., Boulange et al., 2023; Busschaert et al., 2022; Gu et al., 2023; He et al., 2023; Yun et al., 2021).

2.3. Scenario Selection

To most efficiently represent the variety of flood magnitudes that occur on the Barotse Floodplain due to interannual variation, data were separated into decades for analysis. This approach also enables an examination of how flood patterns might evolve over time in the near-, mid-, and far-future. Data were adjusted to the hydrological year of the Zambezi, which begins on the 1st October of the preceding year. Two baseline scenarios were selected from historical data: the 1990s (1-Oct-1989 to 30-Sept-1999) and the 2000s (1-Oct-1999 to 30-Sept-2009). These baseline scenarios were selected as they represent the two most recent decades with a complete 10 years of climate forcing information in the ISIMIP 3b historical database. Additionally, the two decades were selected as they represent different conditions capturing the range of historical variability: the 1990s experienced the lowest average annual precipitation from 1950 to 2016 making it a representative baseline for a drier climate scenario, whereas the 2000s had precipitation close to the long-term average for Zambia (Libanda et al., 2020). Future climate data for each SSP were split into three decades to represent near-future (2030s), mid-future (2050s), and far-future (2070s).

2.4. Hydrological Modeling

The HydroMAD (HYDROlogical Modeling Assessment and Development) *R* package (Andrews et al., 2011) was used to obtain modeled discharge data. As the five sub-catchments of the Upper Zambezi (Figure 1) cover an expansive spatial area and contribute inflows to the Barotse Floodplain at different times, individual lumped rainfall-runoff models were created for each, with calibration and validation computed on the respective tributaries. Sub-catchment delineations were obtained from HydroATLAS (Lehner et al., 2022; Linke et al., 2019). Lumped models have fewer parameters than their semi-distributed and distributed model counterparts, and the parameters of a lumped model instead represent simple spatially averaged catchment characteristics. This approach was deemed most appropriate to represent the sub-catchments due to data limitations arising from inadequate hydro-meteorological measurements (Beilfuss, 2012; Gumindoga et al., 2019; Makungu & Hughes, 2021; Valdés-Pineda et al., 2021; Zimba et al., 2018).

The IHACRES structure (Jakeman & Hornberger, 1993) was selected as it is a hybrid metric-conceptual rainfall-runoff model demonstrating good performance in rainfall-runoff simulation, and its computational and parametric efficiency facilitate its use in climate change impact studies (Croke, 2006; Croke & Jakeman, 2008; De Souza Dias et al., 2018; Jakeman et al., 1990; Moghadam et al., 2023; Ye et al., 1997).

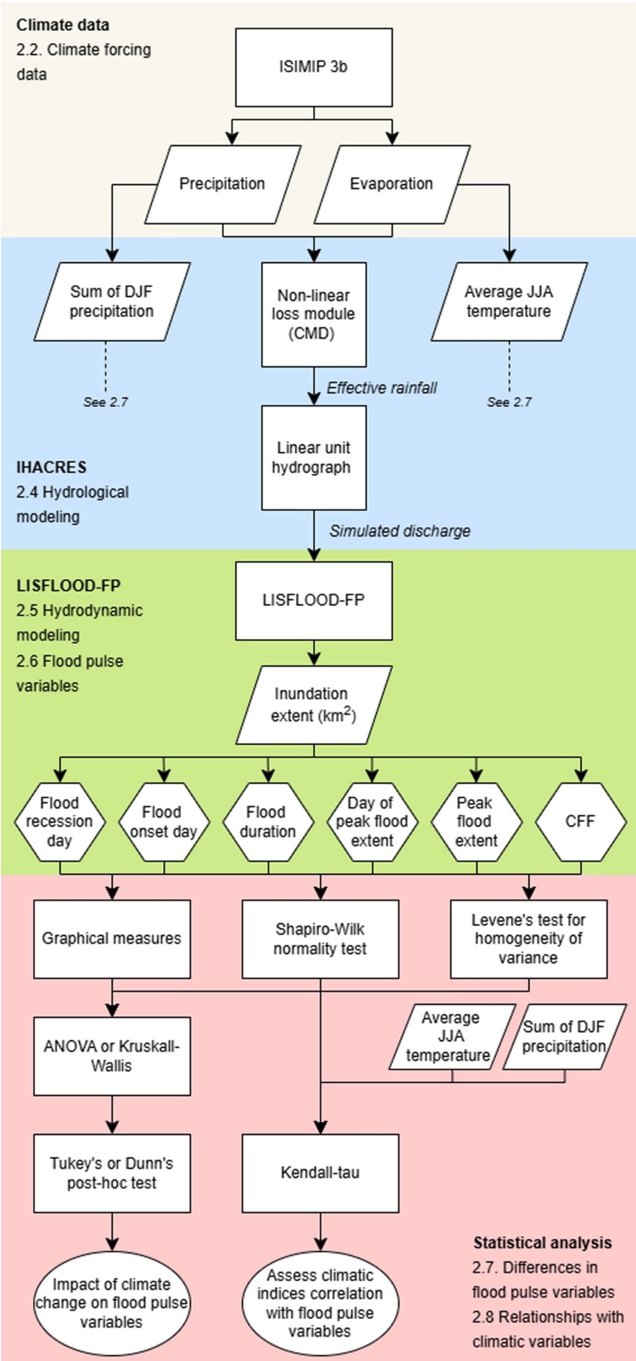

Figure 2. Simple schematic outlining the methodology.

IHACRES is composed of a non-linear loss module (Catchment Moisture Deficit, CMD) to transform observed rainfall into effective rainfall (Equation 1), and a linear instantaneous unit hydrograph to convert the effective rainfall into discharge (Figure 2) (Croke & Jakeman, 2004; Jakeman et al., 1990). The unit hydrograph does not describe the streamflow generation process, but instead models the lumped response of discharge to precipitation; effective rainfall is linearly converted to discharge (Jakeman et al., 1990). Each sub-catchment model contains one lumped exponentially decaying store, the most parsimonious structure for the linear unit hydrograph module. This structure, whilst not physically representative of a catchment, has been shown to be very effective in reproducing observed discharge (Jakeman et al., 1990).

Rainfall effectiveness is a simple instantaneous function of CMD, and the exponential form was used in all five sub-catchment models. Transfer functions relate evapotranspiration and effective rainfall to CMD, and evapotranspiration is a simple function of CMD after precipitation and drainage have been accounted for (Croke, 2006). IHACRES assumes potential evapotranspiration (PET) to be approximately proportional to daily maximum temperature based upon the work of Chapman (2001) with a calibration coefficient used to stabilize this relationship.

$$C_t = C_{t-1} - P_t + ET_t + U_t \tag{1}$$

Equation 1. The CMD model used to calculate changes in moisture over time in the catchment, where C_t is the CMD (mm) constrained by the nominal fully saturated level (0 mm), P_t is the catchment-averaged precipitation (mm), ET_t is the catchment-averaged evapotranspiration (mm), U_t is the effective rainfall (mm) and t represents the timestep.

Observed discharge data were provided by the Water Resources Management Authority (WARMA) of Zambia. It was not possible to select the same calibration and validation period for each sub-catchment, as gauges were asynchronous in recording periods. Additionally, data were subject to continuity issues and gauge measurement errors which required correction where possible; linear interpolation were used for short data gaps in measurements, as has been done successfully in other studies (Timpe & Kaplan, 2017). Five years were selected for calibration for the Upper Zambezi, Kabompo, and Lugwebungu sub-catchments, and 4 years for the Luanginga as this comprised the most continuous set of daily measurements at the gauge. The calibration of the Luena was restricted by its complex hydrology compared to the Barotse Floodplain, whereas in the Luena, shallower floodwaters persistently inundate for longer durations; this proves difficult to represent in hydrological models due to the gauge being situated upstream of the wetland. The Luena was thus calibrated using available, continuous gauge measurements covering the 2018 floodwave, as this was shown to produce a reasonable calibration response in a previous study (Willis et al., 2022).

Each sub-catchment model structure was calibrated using the SCE algorithm, with Kling Gupta Efficiency (KGE) as the objective function. KGE was selected as it is composed of correlation, bias, and variability terms (Kling et al., 2014). Goodness-of-fit were assessed using KGE, Nash-Sutcliffe Efficiency (NSE), bias, and Root Mean Square Error (RMSE) in addition to graphical techniques to ensure observed seasonal patterns are adequately recreated (Arnell, 1996; Bowling & Strzepek, 1997).

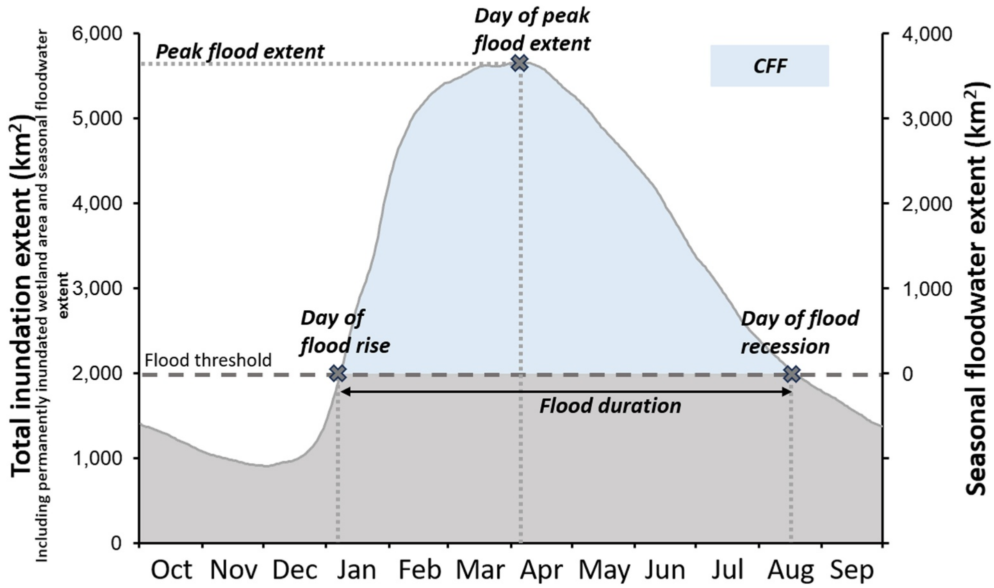

Figure 3. Flood pulse parameters derived for the Barotse Floodplain collectively representing flood amplitude, duration, and timing as adapted from Welcomme and Halls (2004). The threshold which denotes flooding was determined to be ∼2,000 km^2 specific to the Barotse Floodplain. The example flood curve shown is data representative of 2006 on the Barotse Floodplain taken from ISIMIP 3B.

2.5. Hydrodynamic Modeling

The discharge outputs from the hydrological models were input into LISFLOOD-FP (Bates & De Roo, 2000; Bates et al., 2010), a hydrodynamic inundation model applied at a spatial resolution of 900 m. The model was set-up to represent the Baroste Floodplain, and is configured to represent the hydrological processes operating on the floodplain, assuming that flows are mostly subcritical and low velocity (Willis et al., 2022). Terrain data were obtained from the high-resolution TanDEM-X1 digital elevation model (DEM) from 2016, which has a vertical accuracy of 2 m on the floodplain, and a native resolution of ∼12 m (Böer et al., 2008; Wessel et al., 2018). The data were resampled to 100 m to reduce computational costs, which also reduced random noise error, resulting in an improved vertical accuracy of 0.25 m for the 100 m cells.

The model was calibrated and validated using gauge data from WARMA and flood extents derived from Landsat (30 m spatial resolution). Willis et al. (2022) demonstrated that the flood model reproduced the key characteristics of the large floodwave in 2018, with best performance at the flood peak (goodness of fit, $F^2 = 0.62$). The model exhibited lower performance at intermediate flood stages ($F^2 = 0.10$); however, this likely reflects issues with validation using a remotely sensed flood extent derived from Landsat. Optical sensors are unable to detect vegetated waters, thus denoting them as "false negative inundation" during validation, when they are likely truly inundated (Hardy et al., 2020). LISFLOOD-FP produced monthly raster outputs of floodwater depth (*m*) and floodwater velocity (m s^{-1}) with a spatial resolution of 900 m, in addition to daily estimates of floodplain inundation extent (km^2).

2.6. Flood Pulse Variables

From the outputs of the hydrodynamic modeling, flood pulse variables were derived for each individual hydrological year of each scenario (Figure 3). Flood pulse variables are a way of representing the important characteristics of a flood pulse, such as amplitude, duration, and timing (Junk & Wantzen, 2006; Welcomme & Halls, 2004). Previous studies (Melack & Coe, 2021; Timpe & Kaplan, 2017) have selected flood pulse variables specifically to relate them to ecological functions of interest. Here, six flood pulse variables were selected to characterize the Barotse Floodplain's floodwave: (a) flood rise day; (b) flood recession day; (c) flood duration (days); (d) day of peak flood extent; (e) area of peak flood extent (km^2); (f) cumulative spatio-temporal flood extent (km^2•days), hereby defined as Cumulative Flood Footprint (CFF). These variables were deemed to adequately allow assessment of variability, in addition to being significant to health access in understanding how

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changing flood dynamics could impact accessibility to healthcare facilities during flood events (Mroz et al., 2023). This relationship between flood pulse variables and health access has never been studied, but was highlighted by local health officials of the Barotse Floodplain as a concern.

Flood duration is the total number of days of flooding between the flood rise day and the flood recession day. The flood rise day was defined as the first day in which inundation extent exceeded a threshold value, whilst flood recession day was defined as the last day in which inundation extent exceeded this threshold value. There is no defined guidance for selecting a threshold value to ascertain flood duration and studies rely on anecdotal knowledge of the flood pulse system (Räsänen & Kummu, 2013). A threshold value of ∼2,000 km^2 flood extent was explicitly selected for the Barotse Floodplain, determined through analysis of dry season September inundation extents, to distinguish between permanently inundated wetland area and seasonal floodwater inundation.

The area of peak flood extent provides information on the magnitude of the annual floodwave. However, this provides only a snapshot of magnitude at a specific point in time. Hydrological indices have been derived and used in the literature to indicate the relative magnitude of floods across the two dimensions of amplitude and duration (Welcomme & Halls, 2004). Cumulative Flood Footprint (CFF) is thus a novel metric, specifically designed for to quantify the integrated impact of each annual floodwave over both space and time. It is computed by summing the spatial floodwater extent (km^2) per day through the total flood duration, and is expressed as km^2•days (Figure 3):

$$CFF = \sum_{t=1}^{T} A(t) \times \Delta t$$

where, CFF is Cumulative Flood Footprint (km^2·days), *A(t)* is flood extent at timestep t (km^2), Δt is timestep duration (day), and T is the total number of timesteps.

2.7. Differences in Flood Pulse Variables

The annual data for each flood pulse variable were grouped separately for each decade under each specified SSP scenario. The Shapiro-Wilk normality test (Shapiro & Wilk, 1965) was used to assess whether data were normally distributed, and Levene's test for homogeneity of variance (Levene, 1960) was used to examine the equality of variance. Graphical measures were also employed to visually inspect the distribution of all samples. Significant differences in flood pulse variables between each baseline decade and the future decades belonging to each SSP scenario were then assessed. Analysis of variance (ANOVA) (Fisher, 1992) was used to assess differences in means where all samples in a test set-up did not violate the normality and homogeneity assumptions, with Tukey's post hoc test (Tukey, 1949) applied to identify pairwise differences where a significant ANOVA result was obtained. Where data violated normality and homogeneity assumptions, Kruskall–Wallis (Kruskal & Wallis, 1952) was used to identify differences in central tendencies, with Dunn's post hoc test (Dunn, 1961) used for pairwise comparisons where a significant Kruskall–Wallis result was obtained.

2.8. Relationships With Climatic Variables

DJF constitute the months in which the majority of precipitation falls that contributes to the floodwave. For each hydrological year, the sum of DJF precipitation for all five sub-catchments was calculated and its contribution to the seasonal floodwave explored by employing Kendall-tau tests (Kendall, 1938) to assess whether the sum of DJF precipitation shared a relationship with day of flood rise, day of flood peak, peak magnitude, or CFF. Similarly, June, July, and August (JJA) are the months in which flood recession occurs, and in which PET is expected to have influence over the rate of flood recession. In the absence of data on PET, temperature was used as a proxy. The relationship between the average temperature of JJA (PET proxy) over the Barotse Floodplain model domain and the day of flood recession was explored using Kendall-tau tests. All statistical analyses were carried out in Python with a significance level set to $p = 0.05$.

2.9. Assessment of Validity of Baseline Simulations

As part of its third simulation protocol, ISIMIP also provide a historical reanalysis product (ISIMIP 3a) for usage in impact model evaluation and detection of observed impacts. ISIMIP 3a is limited to historical reanalysis for model evaluation, compared to ISIMIP 3b which is specifically designed to provide a consistent framework for quantifying impacts across historical and climate simulations. ISIMIP 3a is based on ERA5 observational climate forcing, and the dataset selected was the W5E5 merged dataset which combines WFDE5 data over land with ERA5 data over ocean (Lange et al., 2023). The bias adjustments applied to ISIMIP 3a were identical to those applied to ISIMIP 3b.

The ISIMIP 3a reanalysis dataset was used to produce a comparative set of simulated historical floodwaves to compare against the ISIMIP 3b GCM-simulated dataset, to assess how well the latter could reproduce baseline simulations in accordance with reanalysis observations. Daily projections of total precipitation and near-surface air temperature were obtained from the ISIMIP 3a protocol between the 1st October 1989 and the 30th September 2019, covering the two baseline scenarios available in the ISIMIP 3b analysis, with an additional decade covering the 2010s also analyzed. These data were similarly used as inputs into the same coupled hydrological-hydrodynamic modeling framework as the ISIMIP 3b data to produce equivalent outputs. The assessment consisted of a comparison of the baseline decadal floodwave variability, as modeled by the different ISIMIP 3a and 3b datasets. Additionally, information on known historical floods and droughts in the Barotse Floodplain were collated, so that the ability of both datasets to model hydrological extremes could be assessed to determine if they had been adequately represented.

3. Results

3.1. Differences in Flood Pulse Variables

A significant difference under climate change between the two baseline decades and the future decades of all scenarios was found for all flood pulse variables (day of flood rise, day of flood recession, flood duration, peak flood extent, and CFF) except day of peak flood extent (Figure 4; Table 1).

Future decades show a later flood rise, resulting in floods shifting to occur later in the hydrological year. The difference is more significant when comparing future decades to the 2000s baseline ($p < 0.001$) than the 1990s ($p < 0.025$), likely due to future decades resembling an increasingly arid floodwave which is more similar to the relatively dry 1990s. The difference becomes significant in the 2050s and 2070s in all climate change scenarios (Figure 4).

In future decades, flood recession occurs earlier in the hydrological year compared to both baseline decades (Table 1). In both SSP 1–2.6 and SSP 3–7.0, the earlier days of flood recession are significant in the 2050s and 2070s compared to either of the baseline decades (Figure 4). Additionally, in SSP 3–7.0, the 2030s is also considered to have significantly earlier flood recession compared to both baseline decades (Figure 4). However, in SSP 5–8.5, only the 2050s are considered significantly different to the baseline decades (Figure 4).

Due to the pattern of later flood rise and earlier flood recession, flood durations are significantly shorter in future decades compared to the baseline decades (Table 1; Figure 4). When compared to the 1990s baseline, significantly reduced flood durations are found for all three decades of all three climate change scenarios. When compared to the 2000s baseline, significantly reduced flood durations are found for all decades except the 2030s in SSP 1–2.6, and the 2030s and 2070s in SSP 5–8.5.

Future decades have a lower peak flood extent than the baseline decades. In SSP 1–2.6, this pattern is only significant in the mid- and far-future (2050s and 2070s). However, in SSP 3–7.0, all future decades exhibit statistically significant lower flood peak extents compared to the baseline decades. In SSP 5–8.5, the 2050s is the only decade to have significantly lower peak flood extents compared to the baseline decades (Figure 4), and is also considered to have significantly lower peak flood extents than the 2070s.

Future decades have lower values of CFF compared to the baseline, indicating spatio-temporal magnitude is reduced as expected, due to the significant decreases in peak flood extent and reduced flood durations. The significant difference patterns are the same as discussed for peak flood extent.

Based on the analysis of differences in flood pulse variables between future and baseline decades, three key patterns emerge: (a) a general reduction in flood durations; (b) altered timings of flood rise and flood recession; (c) reduced flood magnitudes.

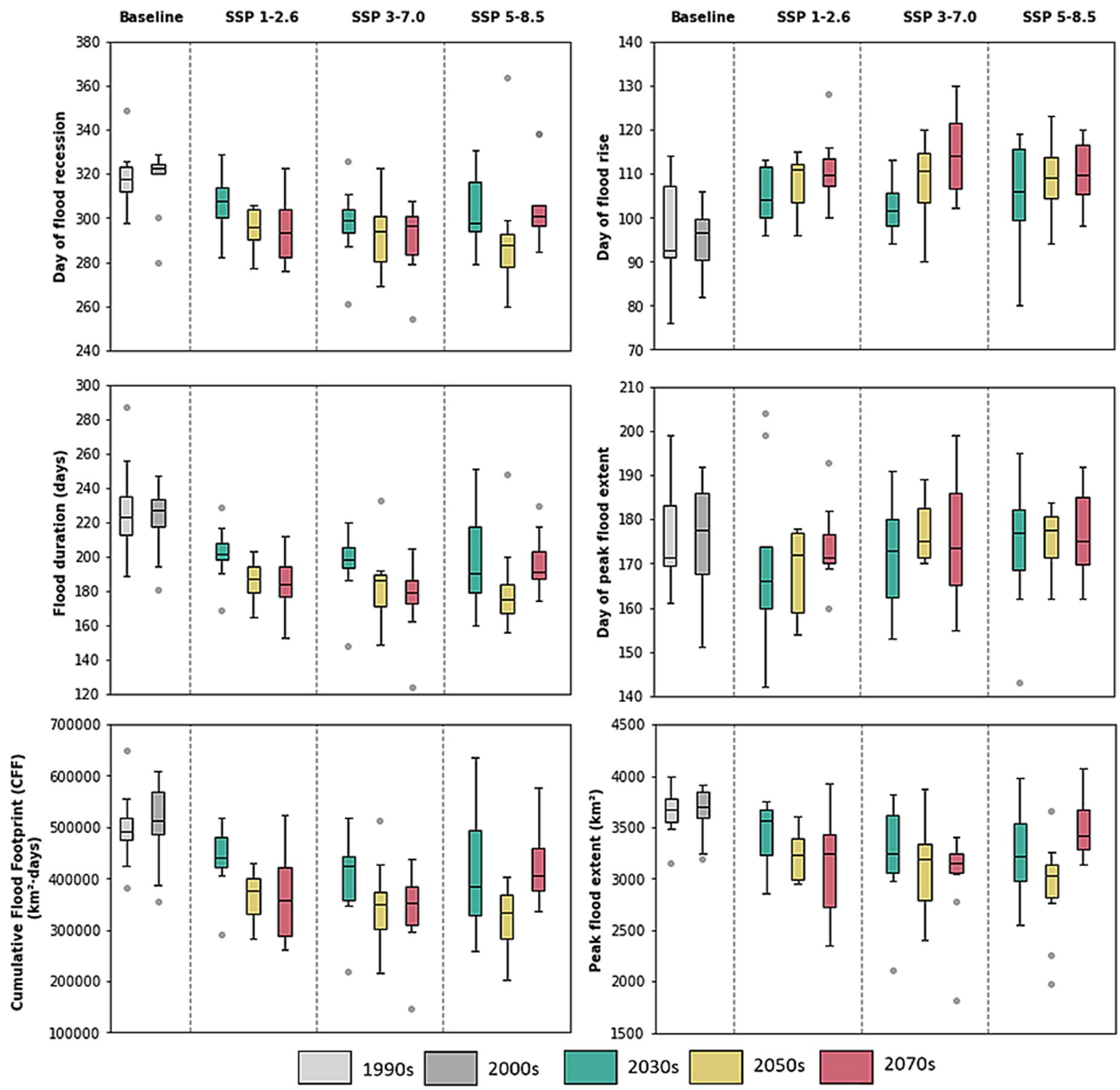

Figure 4. Differences in flood pulse variables between the baseline decades and future decades under three different Shared Socioeconomic Pathways (SSP) scenarios.

3.2. Spatial Pattern of Changes

The reduction in flood durations affect all areas of the Barotse Floodplain (Figure 5) across all decades of all climate change scenarios. Across the floodplain, these changes are typically in the range of −1 to −2 months inundation frequency, with more significant declines evidenced in some decades of up to −3 and −4 months in the north-western region and along the floodplain escarpment. There is an evident distinction in flood inundation duration changes between the Barotse Floodplain and the Luena Valley, highlighting increased sensitivity of the Luena Valley to climate change. The Luena Valley experiences comparatively greater reductions in inundation duration, with average reductions as great as −5 months in the 2050s of SSP 5–8.5. The spatial trend generally indicated an increased aridity occurring across both the Barotse Floodplain and the Luena Valley, which increases in severity with time. The exception is the 2070s of SSP 5–8.5, wherein the reductions in inundation frequency are the least severe of any decade in that scenario, and wherein the Luena exhibits no visual difference resulting from increased sensitivity compared to the Barotse Floodplain.

Reduced average flood extents are evidenced across the entire model domain; however, the reductions are more spatially asynchronous than inundation duration changes (Figure 6). Flood cells across the floodplain exhibit a

Table 1
Statistical Comparison of Differences in Flood Pulse Variables Between Baseline Periods and Future Climate Change Scenarios, With Near- (2030s), Mid- (2050s), and Far-Future (2070s) Decades Grouped Together Within Each Shared Socioeconomic Pathways (SSP) Scenario

		SSP 1–2.6		SSP 3–7.0		SSP 5–8.5	
	Baseline period	*p*	*Test Statistic*	*p*	*Test Statistic*	*p*	*Test Statistic*
Day of flood rise	1990s	0.025* (50s, 70s)	H 9.319	0.00100*** (50s, 70s)	F 6.749	0.021* (50s, 70s)	F 3.657
	2000s	0.001*** (30s, 50s, 70s)	H 15.66	0.000063*** (50s, 70s)	F 9.990	0.0026** (50s, 70s)	F 5.717
Day of flood recession	1990s	0.00072*** (50s, 70s)	F 7.106	0.0011** (30s, 50s, 70s)	F 6.613	0.0049** (50s)	H 12.90
	2000s	0.0070*** (50s, 70s)	H 12.12	0.0083** (30s, 50s, 70s)	H 11.74	0.014* (50s)	H 10.63
Flood duration	1990s	0.000036*** (30s, 50s, 70s)	F 10.71	0.000077*** (30s, 50s, 70s)	F 9.723	0.0033** (30s, 50s, 70s)	H 13.75
	2000s	0.000047*** (50s, 70s)	F 10.36	0.00014*** (30s, 50s, 70s)	F 8.970	0.0063** (50s)	H 12.34
Cumulative flood footprint	1990s	0.00031*** (50s, 70s)	F 8.057	0.00024*** (30s, 50s, 70s)	F 8.359	0.00077*** (50s)	F 7.025
	2000s	0.00024*** (50s, 70s)	F 8.360	0.00017*** (30s, 50s, 70s)	F 8.778	0.00061*** (50s)	F 7.295
Day of flood peak	1990s	0.54	H 2.151	0.69	F 0.4898	0.98	F 0.0513
	2000s	0.49	F 2.397	0.75	F 0.4073	0.98	F 0.0532
Peak flood extent	1990s	0.0063** (50s, 70s)	H 12.36	0.0059** (30s, 50s, 70s)	H 12.49	0.016* (50s)	F 3.936
	2000s	0.0077** (50s, 70s)	F 4.629	0.0079** (30s, 50s, 70s)	H 11.84	0.016* (50s)	F 3.902

Note. For each variable, the specific future decades showing significant differences compared to the baseline periods are indicated in parentheses underneath the *p*-values. Test statistics are denoted as H for Kruskall–Wallis and F for ANOVA. Significance levels are indicated by * for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$.

variety of declines in flood frequency; however, reduced flood extents predominate in the north, along the western escarpment, and in the Luena Valley where changes are more spatially contiguous. The trend is typically for reduced extents, with areas of up to 52 km^2 exhibiting a complete loss of annual inundation in a future decade (change of −10 years). However, in the 2030s in SSP 1–2.6, and in the 2030s and 2070s in SSP 5–8.5, small proportions of the floodplain (between ~20 and 160 km^2) exhibit increases in flood extent; these are primarily up to 2 years, with very few areas (no greater than 18 km^2) exhibiting changes up to no more than 4 years.

3.3. Link to Climatic Variables

To explain the variation occurring between baseline and future decades for the different flood pulse variables, the relationship between precipitation and temperature were explored (Table 2; Table 3). Relationships between variables were first assessed using an aggregated dataset combining all decades and scenarios in order to capture overarching trends (referred to as “the entire dataset”), before a decade-based analysis was conducted to allow detection of changes in relationships that may otherwise be obscured by assessment over the longer period; this permitted a more nuanced understanding of how varying climate conditions influence flood dynamics over specific decades.

Across the entire dataset, the relationship between the sum of DJF precipitation and the day of flood rise was significant ($p < 0.001$, $\tau_\beta = -0.21$) evidencing greater DJF sums correlate to earlier days of flood rise. However, when examining specific decades and scenarios, only in the 2000s baseline decade, and in the 2030s of SSP 1–2.6 and SSP 5–8.5 was a greater sum of DJF precipitation significantly correlated with an earlier day of flood rise (Table 2).

Overall, greater DJF precipitation amounts resulted in larger CFF ($p < 0.001$, $\tau_\beta = 0.22$) and peak flood extents ($p < 0.001$, $\tau_\beta = 0.23$), albeit this varied by decade and scenario. In both baseline decades and all decades in SSP 1–2.6, a greater sum of DJF precipitation is significantly associated with a greater CFF (Table 2). In SSP 5–8.5, the 2030s also exhibits larger flood CFF values in response to larger sums of DJF precipitation ($p < 0.001$, $\tau_\beta = 0.82$). However, no significant relationship is evidenced in SSP 3–7.0, or in either the 2050s or 2070s of SSP 5–8.5, albeit coefficient values evidence a positive non-significant relationship between increased DJF precipitation and greater CFF (Table 2). Likewise, the same patterns exist between the sum of DJF precipitation and peak flood extent for each respective climate scenario and decade, with the exception of the 1990s where the significance drops below the 95% percentile ($p = 0.07$, $\tau_\beta = 0.46$). There was no significant relationship between DJF

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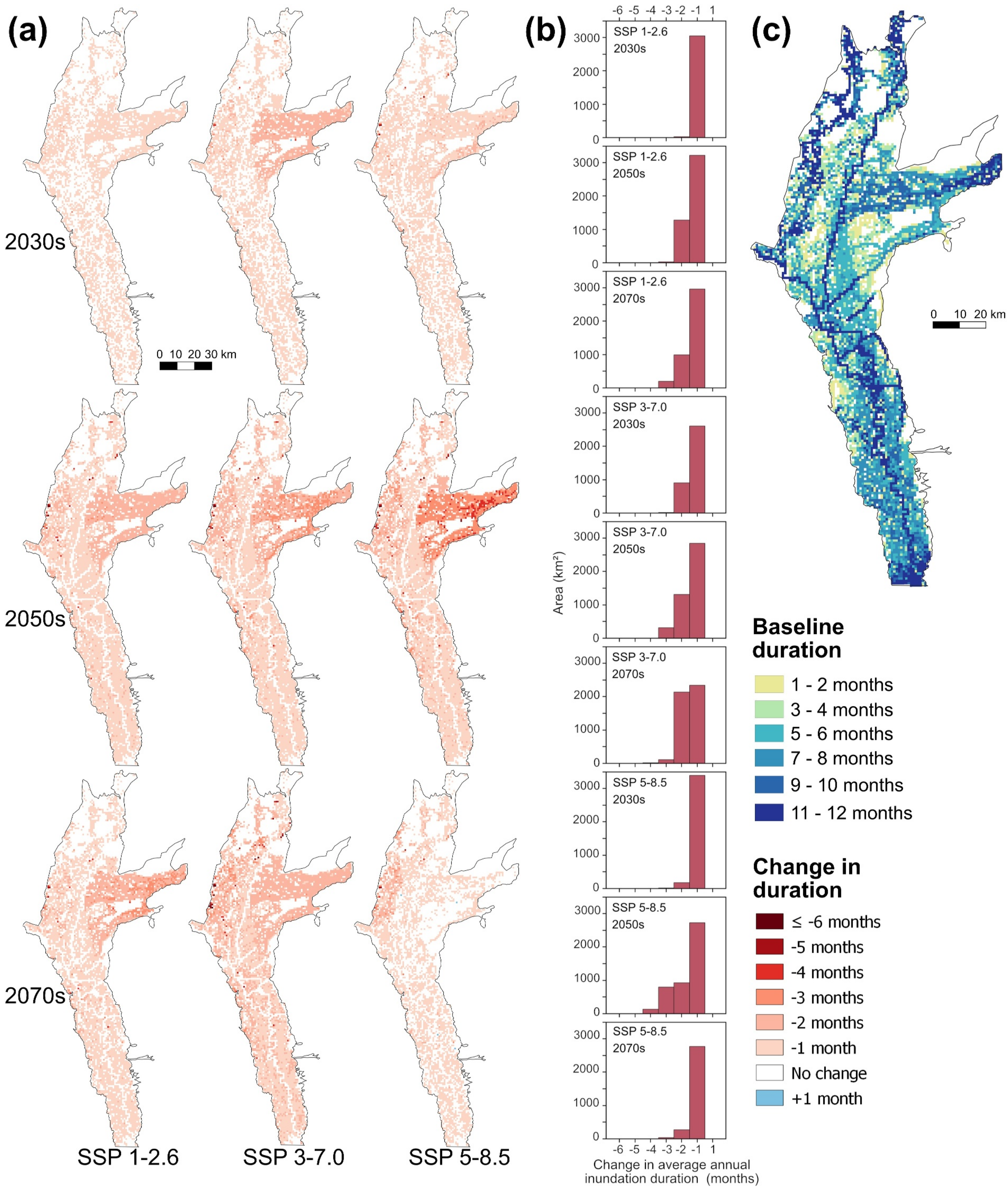

Figure 5. Changes in future inundation duration of an average floodwave, respective to the 2000s baseline. (a) Matrix of maps representing the average of the decadal spatial changes in number of months of inundation duration across the floodplain. (b) Histograms quantifying the areas of inundation duration change (in km^2) for each decade of each climate change scenario, relative to the 2000s baseline. (c) Average duration of floods during the 2000s baseline decade.

sums and day of peak flood occurrence across the entire dataset ($p < 0.76$, $\tau_\beta = -0.02$) or when assessing by specific decade and scenario (Table 2). Weak, negative τ_β directions suggest a generally non-significant pattern of increased sum of DJF precipitation resulting in an earlier day of peak flood occurrence.

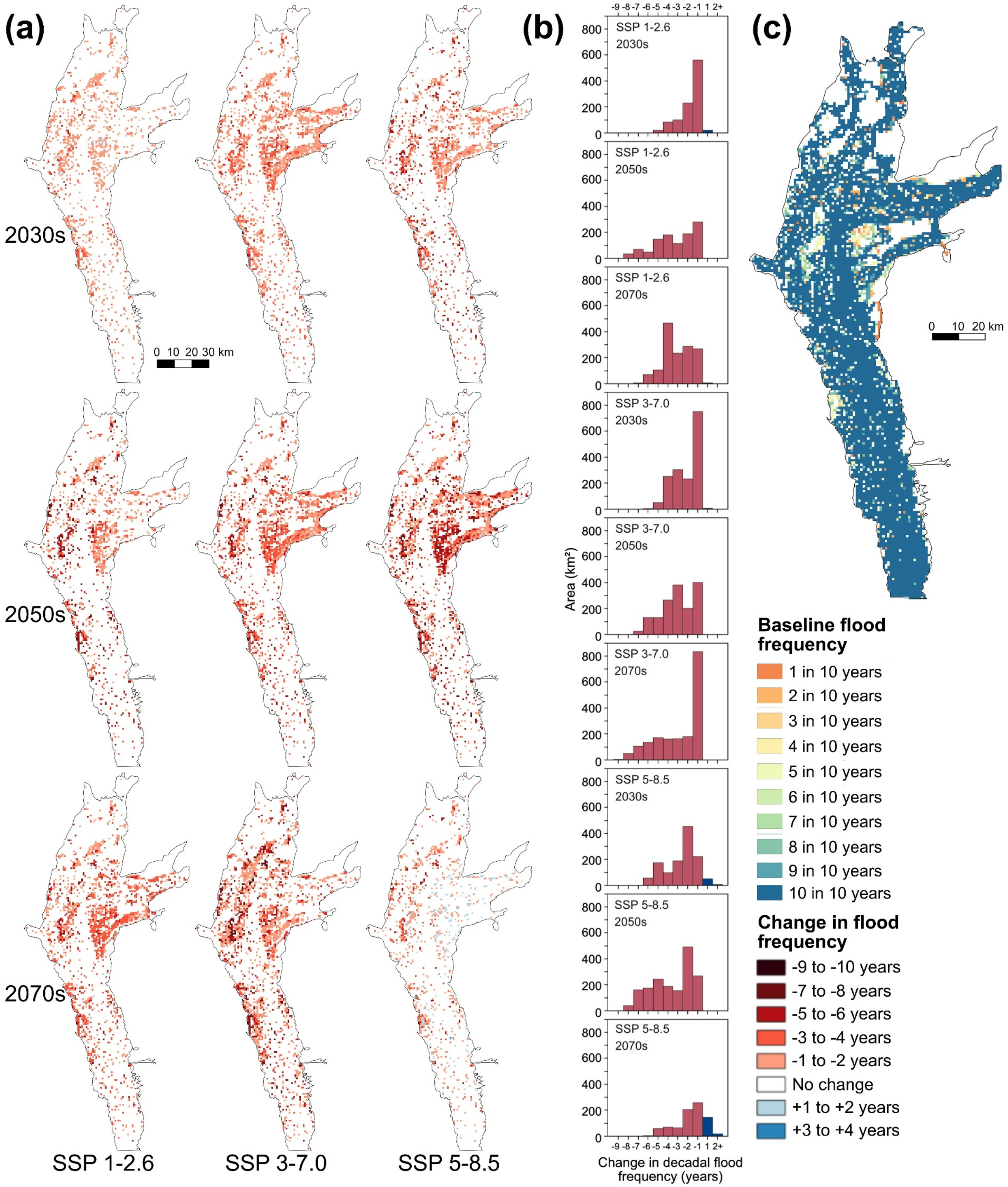

Figure 6. Changes in flood frequency (number of years in each decade a floodplain cell was flooded) respective to the 2000s baseline. (a) Matrix of maps representing the spatial change in flood frequency across the floodplain in future decades. (b) Histograms quantifying the total area (km^2) of the floodplain for which flood frequency has changed for each decade of each climate change scenario. (c) Flood frequency for the 2000s baseline decade.

Correlations were investigated between average JJA temperature and day of flood recession, to variable significance across the climate scenarios and decades. Higher average JJA temperatures are significantly linked to earlier flood recessions in the 1990s, as well as in the 2030s and 2070s in SSP 1–2.6, the 2050s in SSP 3–7.0, and the 2070s in SSP 5–8.5 (Table 3). Whilst no significant relationships were found for the remainder of decades, a

Table 2
Analysis of Relationship Between Sum of December, January, and February (DJF) Precipitation and Four Flood Pulse Parameters DJF Precipitation Has Influence

		Day of flood rise		Cumulative flood footprint		Day of flood peak		Peak flood extent	
Sum of DJF pr		p	τ_β	p	τ_β	p	τ_β	p	τ_β
Baseline	1990s	0.42	−0.20	0.047*	0.51	0.47	−0.18	0.073	0.47
	2000s	0.029*	−0.56	0.047*	0.51	0.60	−0.16	0.029*	0.56
SSP 1–2.6	2030s	0.038*	−0.52	0.0091**	0.64	0.79	−0.068	0.047*	0.51
	2050s	0.32	−0.25	0.00012***	0.87	0.20	0.32	0.0091**	0.64
	2070s	0.28	−0.27	0.0091**	0.64	0.21	−0.31	0.0091**	0.64
SSP 3–7.0	2030s	0.59	−0.13	0.22	0.33	0.11	−0.42	0.29	0.29
	2050s	0.16	−0.38	0.29	0.28	0.13	−0.39	0.11	0.42
	2070s	0.073	−0.47	0.22	0.33	0.60	−0.16	0.48	0.2
SSP 5–8.5	2030s	0.00095***	−0.78	0.00036***	0.82	0.48	−0.2	0.00036***	0.82
	2050s	0.48	−0.2	0.73	0.11	0.32	−0.25	0.86	−0.067
	2070s	0.11	−0.40	0.48	0.2	0.28	−0.27	0.86	0.067
Entire Dataset		0.0016**	−0.21	0.00066***	0.22	0.76	−0.020	0.00034***	0.23

Note. Significance levels are indicated by * for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$. The Kendall tau (τβ) coefficient is used to measure the strength and direction of association between variables. The 'Entire Dataset' row aggregates all decades and scenarios to show the overall relationship.

negative τ_β is consistent, suggesting a weak, non-significant pattern of earlier recession associated with increased JJA temperatures. Across the entire dataset, higher JJA temperatures were statistically linked to earlier flood recessions ($p < 0.001$, $\tau_\beta = -0.385$). The decadal analysis evidences more nuanced relationships between JJA temperatures and flood recession, with significant variability existing between decades and scenarios.

Table 3
Analysis of Relationship Between the Mean of June, July, and August (JJA) Temperature and Day of Flood Recession

		Day of flood recession	
Mean of JJA temperature		p	τ_β
Baseline	1990s	0.018*	−0.60
	2000s	0.53	−0.16
SSP 1–2.6	2030s	0.0052**	−0.70
	2050s	0.087	−0.43
	2070s	0.0022**	−0.73
SSP 3–7.0	2030s	0.59	−0.13
	2050s	0.0091**	−0.64
	2070s	0.073	−0.47
SSP 5–8.5	2030s	0.058	−0.48
	2050s	0.32	−0.25
	2070s	0.046*	−0.51
Entire Dataset		3.5e−9***	−0.38

Note. Significance levels are indicated by * for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$. The Kendall tau (τ_β) coefficient is used to measure the strength and direction of association between variables. The 'Entire Dataset' row aggregates all decades and scenarios to show the overall relationship.

3.4. Assessment of Validity of Baseline Simulations

The simulations of floodwaves in the 1990s and 2000s baseline periods, as modeled separately by ISIMIP 3a and ISIMIP 3b, were compared against Musonda et al. (2020)'s reported droughts and severe pluvial events over Zambia. Musonda et al. (2020) used a standardized precipitation index to assess long-term variations in drought characteristics, and showed that Zambezi experienced significant droughts in 1991–1992, 1994–1995, 2005–2006, and 2015–2016, all of which are captured in ISIMIP 3a simulated floodwaves where annual maximum flood extents in these drought years do not exceed 2,500 km^2. Similarly, the ISIMIP 3a simulated floodwaves captures the larger flood years of 2007, 2010, 2011, and 2017, which were considered to be severe pluvial years, with flood extents exceeding 4,000 km^2. However, ISIMIP 3b does not recreate historical floodwave extremities. There is a narrower band of decadal flood variability in ISIMIP 3b compared to ISIMIP 3a (Figure 7); peak extents in ISIMIP 3b all occur within the range of 3,000 km^2 to 4,000 km^2 whereas in ISIMIP 3a the range is between ~1,750 km^2 to ~4,500 km^2. Observed historical hydrological extremes are not obvious in the ISIMIP 3b dataset and are instead constrained within the variability of normal flood years (Figure 7).

4. Discussion

4.1. Key Findings and Broader Implications

Previous work conducted across the Zambezi basin has focused on projecting changes in precipitation and runoff under climate change (Arnell, 1999; Boko

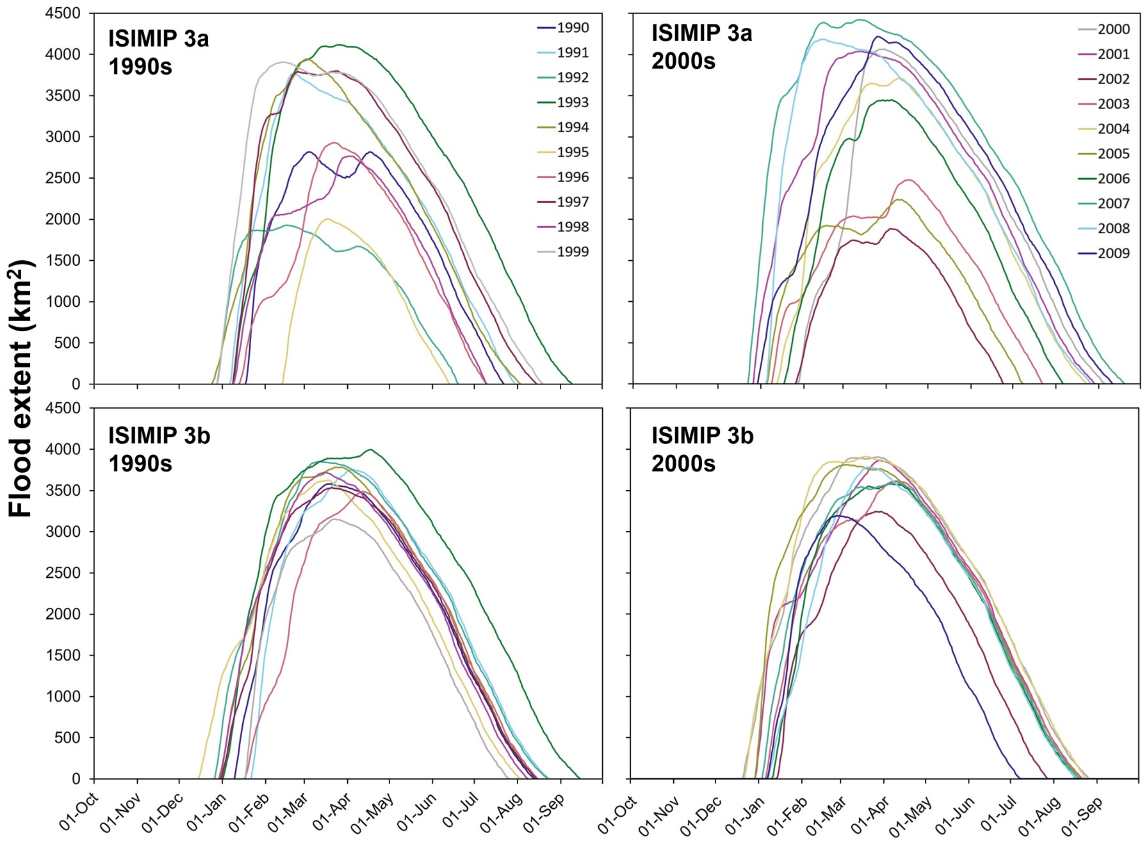

Figure 7. Simulations of individual flood years in the 1990s and 2000s baseline decades compared between the Inter-Sectoral Model Inter-Comparison Project 3a and 3b datasets.

et al., 2007; De Wit & Stankiewicz, 2006; Eriksson et al., 2015; Fant et al., 2015; Gannon et al., 2014; Hamududu & Ngoma, 2019; IPCC, 2001; Libanda & Ngonga, 2018; Maúre et al., 2018; Tadross et al., 2009; Zeng et al., 2019) albeit generally lacking consensus on the direction of changes. Whilst important, the resultant floodwaves in the Zambezi basin have remained understudied, despite the potential risks to the livelihoods of local people should variability diverge from what is historically observed. This study is the first to directly model how climate change may affect flood pulse variables in the Barotse Floodplain. Flood duration and flood magnitude (both peak and cumulative, CFF) are demonstrated to decrease under future climate change compared to baseline scenarios, with these decreases significant in the mid-to far-future. This finding is substantial in stating an expectation that the average annual floodwave on the Barotse Floodplain will become shorter, with reduced inundation extents, resulting in increased aridity in the future. The reduction in flood durations originates from the floodwave arriving later in future decades but with the flood recession also occurring earlier, indicating a shift in timing. There is also potentially a shift in the shape of the floodwave itself due to the timing, duration, and magnitude, all demonstrating significant changes.

4.2. Implications for the Barotse Floodplain

These modeled impacts to the floodwave's characteristics have the potential to alter significantly the local livelihoods of the Lozi. The Lozi rely on their own, sophisticated early warning systems to estimate flood rise, flood peak, and flood recession (Mapedza et al., 2022). For example, a beetle known as *Tumbombo* is used to indicate whether floodwaters are rising, maintaining water level, or receding, based on their orientation on river vegetation (Mapedza et al., 2022; Singini, pers. comm.). Whilst the beetle faces upstream, in the direction opposite to the flow, communities determine the flood level is still rising, but once it faces downstream, communities expect that the peak of the annual flood event has occurred, which signals them to begin crop cultivation (Mapedza et al., 2022). Unexpected variability has already been demonstrated to disrupt these early warning systems and their usefulness. In 2023, the floodwave peaked early and began to recede with *Tumbombo*

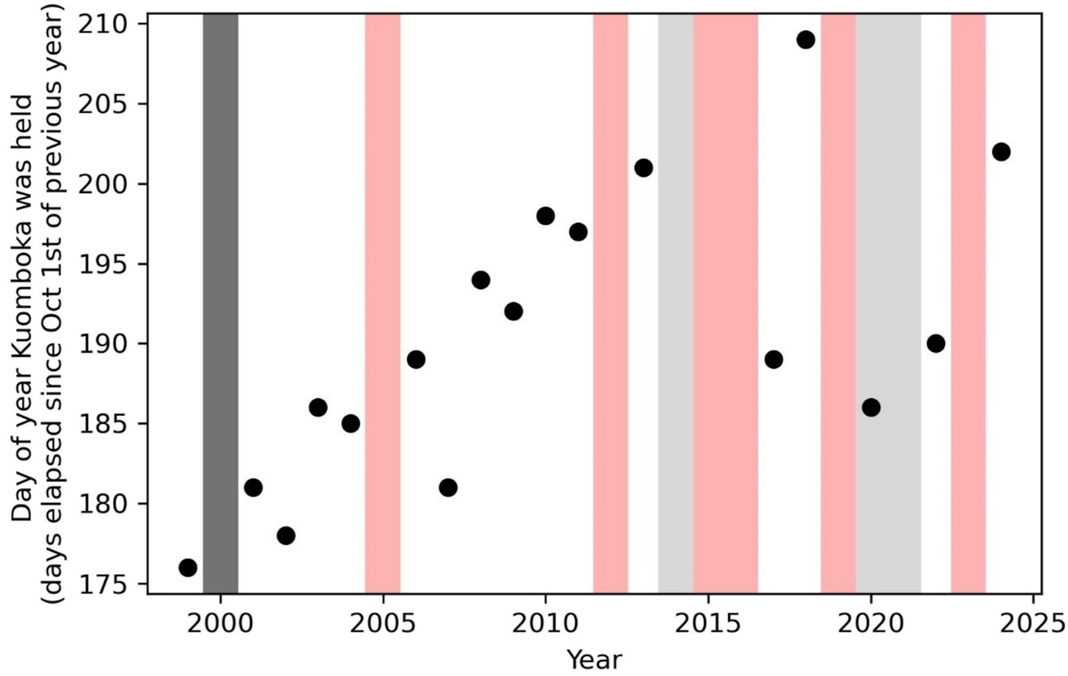

Figure 8. Kuomboka occurrence from 1999 to 2024. Black dots denote the day Kuomboka was held. Red bands denote years the Barotse Royal Establishment (BRE) canceled Kuomboka due to low floodwaters. Black bands denote no data, where information on whether the Kuomboka was held could not be sourced. Light gray bands denote cancellation where the BRE cited other reasons, such as bereavement. Note that the 2020 Kuomboka festival was canceled due to the Covid-19 pandemic, but the BRE had already scheduled a date, hence the scheduled Kuomboka date is included in the dataset as it would have otherwise occurred.

positioning changing respectively. In response, the *Kuomboka* ceremony (a historical festival celebrating Lozi transhumance wherein populations vacate the floodplain on canoes for higher grounds) (Flint, 2006) was canceled due to poor flood level, and crop cultivation began. However, the flood levels then began to rise again, resulting in an unusual second flood peak that surprised floodplain residents. Food availability in the Barotse Floodplain is highly seasonal, with the hunger period typically occurring between August and January (Pasqualino et al., 2015). With agriculture being subsistence-based, both droughts and unexpected flood damages to crop cultivation increase hunger and famine, with wider implications of malnutrition. As a result of the 2023 drought and flood resurgence, health officials in April 2023 stated crop cultivation was poor and they expected increased hunger, resulting in increased malnutrition (Mongu and Shangombo District Health Offices, pers. comm.). More attention needs to be dedicated toward understanding these local knowledge systems as they are proven to be previously reliable, and to also understand how climate change will disrupt these flood pattern indicators (Mapedza et al., 2022; Mercer et al., 2010; Ncube & Lagardien, 2015). Analysis of *Kuomboka* occurrences (which takes place around the end of the rainy season) suggests indigenous awareness of changes to the floodwaves already occurring (Figure 8), with increased cancellations due to low floodwaters and the festival data generally shifting to be later in the year. In 2024, amidst severe drought, the Barotse Royal Establishment (BRE) announced a "unique" Kuomboka would be held "in the face of climate change" (Barotse Royal Establishment, 2024) with a change in venue for the ceremony as the traditional route was not possible due to the low floodwaters.

The results of this study demonstrate a likelihood that the annual floodwave of the Barotse Floodplain will trend towards aridity, with shorter flood durations of decreased magnitude. The impacts of aridification and drought are arguably worse than the impact of higher-than-normal magnitude floods (e.g., Sok et al., 2021) and we argue that the projected desiccation of an average floodwave in the region has greater negative impacts to the region's health due to the strong interrelationship between agricultural activities, health, and transport, wherein negative impacts can compound into public health disasters. District health officers have reported concerns that drought leads to hunger which in turn is resulting in people failing to seek healthcare services (Shangombo District Health Office, pers comms).

Whilst there is a dearth of research understanding how seasonal floods affect health (Alexander et al., 2018; Saulnier et al., 2018), it is known they alter prevalence of diseases such as malaria, morbidities, and mortalities, and, by extension, cause changes in care-seeking behavior (Abu-Saymeh, 2023; Alexander et al., 2018; Phung et al., 2014; Sajid & Bevis, 2021; Saulnier et al., 2018). Floods affect health depending on a combination of geographic and population characteristics (Ahern et al., 2005; Du et al., 2010), though repeated exposure is linked to reduced vulnerability (Saulnier et al., 2018). The ability of populations to seek and reach health care is integral to a region's overall health. In the Barotse Floodplain, transport is adapted to the floodwave, with the use of ox-carts and dugout canoes facilitating easier and faster transport during the flood period. By comparison, dry season transport is restricted to walking which is comparatively slower. Hence, we hypothesize that a decline in flood extent and duration will correlate with an increase in travel times across the floodplain. This could have serious implications for continued access to treatment for chronic diseases, such as HIV which Western Province has a high burden, or for maternal care (Mroz et al., 2023). Unexpected variability in flood patterns could also impact the transmission dynamics of malaria, altering the breeding sites of *Anopheles* mosquitoes (Smith et al., 2013, 2024).

The coupled hydrological-hydrodynamic model simulates that these changes will be most impactful in both spatial and temporal variability of inundation in the northern Barotse Floodplain and in the Luena Valley. The Luena Valley has been shown to have a different set of hydrological characteristics compared to the main Barotse Floodplain (Mroz et al., 2023), wherein the floods are shallower and more persistent. Additionally, Oakes et al. (2023) observed from Sentinel-1 radar imagery that historic annual deviations away from the median extent were greatest in the Luena Valley, indicating the region's inundation is highly sensitive to both dry and wet extremes. The future predicted increased aridity of the northern Barotse Floodplain is linked to present-day patterns in which the region typically only floods in larger flood years, hence why it would be expected to flood less under reduced flood extents in the future. Evidently, the flood model is able to adequately represent hydrology in the region, and ISIMIP 3b data are consequently useful in identifying a heightened sensitivity to climate change impacts in the Luena Valley and northern Barotse Floodplain compared to the rest of the floodplain.

4.3. Limitations, Uncertainty, and Future Research Avenues

Whilst the coupled hydrological-hydraulic model evidences a good representation of the hydrological characteristics of the Barotse Floodplain and its tributary valleys, the results of the baseline comparison demonstrate that the ISIMIP 3b data is unable to recreate the historical hydrological extremes of climate that resulted in drought or large floodwaves in the Barotse Floodplain. Thus, the use of ISIMIP 3b data is limited to representing the decadal average of floodwaves, which can be used to assess general trends regarding flood pulse variables. There is limited rain gauge information in the Zambezi basin, resulting in a reliance on satellite-derived rainfall estimates (Schleiss & Matos, 2017). The lack *of in-situ* observed precipitation data creates uncertainty in the hydrological model process (Chomba et al., 2021; Papa et al., 2023). The limited availability and quality issues of *in-situ* hydrological observations are not unique to the Upper Zambezi, and have instead affected model calibration and validation across Africa (Dube et al., 2023).

The inclusion of all five sub-catchments potentially masked an important signal arising from the impacts of climate change on a specific area, such as the Angolan Highlands which has become significantly more drought-vulnerable (Brooks et al., 2005; Cain, 2015; Carvalho et al., 2017; Gore et al., 2020; Lourenco & Woodborne, 2023; Nhamo et al., 2019). Future research should examine the impact of spatio-temporal precipitation variability on the runoff generation, with a specific focus on the Angolan Highlands whose significance extends beyond merely the Barotse Floodplain and affects the entire of Southern Africa (Carvalho et al., 2017; Crétat et al., 2019; Gore et al., 2020; Howard & Washington, 2018; Huntley et al., 2019; Lourenco et al., 2022).

Additionally, the importance of PET has been emphasized in the literature. This directed our attempt to correlate the average temperature of the recession months with flood recession dates. Temperature data was used in lieu of PET data as, at present, PET data is not included in the ISIMIP 3b protocol. Willis et al. (2022) demonstrated that the hydrodynamic model of the Barotse Floodplain was insensitive to the inclusion of PET, and similarly, Gumbricht et al. (2004) arrived at a conclusion that the lack of annual variability in evapotranspiration resulted in no improvement when included in predictive models. Again, the controls over flood recession are more complex than just the average temperature on the floodplain.

The discharge of one hydrological year may impact the lag time between peak discharge and peak flooded area in the following hydrological year, evidenced by Burke (2015). Additionally, cyclic behavior has been identified on the Zambezi River as well as the nearby Okavango and Chobe River (Beilfuss, 2012; Mazvimavi & Wolski, 2006; McCarthy et al., 1998; Moore et al., 2007). The cause of the cyclic behavior remains unknown, but studies (e.g., Long et al., 2014) have been able to link it to relative changes in flood magnitude. Pricope (2013) emphasizes that there may be complex lags and feedbacks in the Barotse Floodplain system that cause period changes in runoff averages. Overall, there is a complexity of controls behind the flood pulse characteristics of the Barotse Floodplain, including natural variability and anthropogenic modifications such as canals and causeways, which further complicate the hydrological dynamics; there is a need to consider these factors when designing suitable methodologies to isolate specific mechanisms without prior knowledge. These issues extend to all African rivers, which are under-studied relative to global research efforts (Alsdorf et al., 2016; Papa et al., 2023) despite their global significance for biodiversity and ecological cycles (Hastie et al., 2021; Lunt et al., 2019; Simaika et al., 2021).

Finally, cascading uncertainty is inherent in the methodology. Uncertainty in the historical and future climate data could propagate into the coupled hydrological-hydrodynamic model. Calibration and validation of the model were optimized to yield the best goodness-of-fit, but the models remain a simplification of reality, with lumped parameterisation of each sub-catchment's hydrological characteristics and limited representation of hydrological and hydrodynamic processes. Furthermore, we encountered challenges in accurately modeling the low flooding extents present at intermediate flood stages, but ongoing advances in remote sensing will enable mitigation of this limitation in the future. Namely, the increasing availability of L-band SAR satellites will greatly enhance the ability to map hydrological dynamics, particularly in areas where dense vegetation inhibits the observation of inundation, such as herbaceous-dominated floodplains and forested wetlands (Oakes et al., 2024).

4.4. Global Significance

This work has global relevance, as the threat of climate change impacts to floodwaves extends to all floodplains elsewhere. Floodplains are one of the most vulnerable environments to the impacts of climate change (Flint, 2008; Pricope, 2013) as are the tens of millions of floodplain dwellers who are dependent on floodplains for their livelihoods (Schöngart & Junk, 2007; Towner et al., 2020). The low adaptive capacity, subsistence-based economies, and high dependency on annual flood pulses compounds the risk of rainfall variability and hydrological extremes due to exacerbation of present vulnerabilities (Flint, 2008; Sherman et al., 2015), creating an amplified sensitivity to climatic impacts. Elsewhere, floodplain dwellers also exhibit sophisticated local adaptations to historical and present floodplain conditions, but these could become inadequate for future variability under climate change (Motsholapheko et al., 2015) resulting in shocks that could impact transportation, health, education, trade, agriculture, and other societal needs (Bauer et al., 2018; Hofmeijer et al., 2013; Pinho et al., 2015). Flood pulses on other rivers such as the Mekong, Congo, Amazon, Okavango, Chobe, and Ganges-Brahamputra are similarly expected to be modified by climate change, with implications for the millions of people who have livelihoods dependent on the functioning of the floodplains (Delgado et al., 2010; Eastham et al., 2008; Kazama et al., 2012; Phung et al., 2016; Västilä et al., 2010).

In the Pervuian Amazon, Langill and Abizaid (2020) emphasized that there is a lack of understanding about extremes of annual floods and local vulnerabilities. Evidently, there is an urgent need to investigate climatic change impacts on floodplains to understand how livelihoods may be impacted. This study's methodology—utilizing readily available data and coupled hydrological-hydrodynamic modeling—demonstrates a robust approach for assessing changes in flood pulse dynamics in a generalized manner for further considering impacts to floodplain livelihoods. Whilst applied specifically to the Barotse Floodplain as a case study, this study is of relevance worldwide and can be replicated to forecast potential climate impacts and inform potential adaptive strategies for vulnerable floodplain communities.

5. Conclusions

Climate change is expected to modify hydrological cycles beyond what has been observed historically; however, little attention has been dedicated toward changes to floodplains and the consequences for indigenous populations. This study is the first to directly model climate change impacts on key flood pulse variables as relevant to local livelihoods on the Barotse Floodplain. Increased aridification of the Barotse Floodplain is expected in the mid-to far-future. This study is the first to evidence changes to the timing of the floodwave, decreased duration, and decreased flood extents. These changes could have severe consequences for the health of the Barotse Floodplain population due to the intricate interrelationships that exist between agricultural activities, health access, and transport. The lack of hydrological understanding in the Zambezi limited efforts to understand the climate change drivers underpinning the changes evidenced. The strong interconnections between floodplain hydrology and tens of millions of human livelihoods across the globe must urgently be understood, as developing efficient management and mitigation efforts will be reliant upon understanding climate change impacts explicitly in their local context.

5.1. Inclusion in Global Research Policy

The Zambian Water Resources Management Agency (WARMA) are thanked for provision of gauge data. In particular, Happiness Malawo, Cosmas Chalo, and Mweemba Sinkombo procured, cleaned, and provided assistance with the usage of the gauge data, and are hereby acknowledged for their substantial contribution as co-authors. We are grateful to our local collaborator Douglas Singini, who provided local information on the floodwave and the Kuomboka festival which helped inform our understanding. We are also especially thankful to the Litunga and the other members of the BRE who graciously spent time in a meeting to discuss their perspectives of climate change impacts on the floodplain as it pertained to people's livelihoods.

Data Availability Statement

Climate forcing data were obtained and are available in the form of NetCDFs from the ISIMIP repository: https://data.isimip.org/ (Lange & Büchner, 2021). These data were clipped by sub-catchment and converted to CSVs, which are available from our repository (Mroz et al., 2024).

The hydrological modeling was conducted in *R* (R Core Team, 2021) within RStudio (RStudio Team, 2020) using the HYDROMAD package, which has a GNU General Public License (Andrews et al., 2011). The specific codes used for the setup, calibration, and validation of our hydrological models are available in our repository, as well as the goodness-of-fit metrics for calibration and validation (Mroz et al., 2024).

The observed discharge data used in calibration and validation were provided by WARMA, which can be requested from https://warma.org.zm/?page_id=1537.

As we do not have permission to share the observed discharge data, we have provided metadata on the stations we used in the repository for transparency (Mroz et al., 2024).

The hydrodynamic modeling was conducted in the LISFLOOD-FP software, which is available under a GNU General Public License v3.0 for any non-commercial use (Bates & De Roo, 2000; Bates et al., 2010). Information on the specific Barotse Floodplain model is available from Willis et al. (2022), who set up and conducted the calibration and validation of the model. We are not able to share the original or processed TANDEM-X DEM due to licensing agreements, but it can be ordered via a proposal submission: https://tandemx-science.dlr.de/cgi-bin/wcm.pl?page=TDM-Proposal-Submission-Procedure.

The outputs from the hydrodynamic modeling are provided in our repository, as well as the processing of raw data into flood pulse variables (Mroz et al., 2024).

We provide the Python code for our statistical analysis in our repository as well as the Python codes used to create any figures (Mroz et al., 2024).

QGIS was used to create all maps (QGIS Development Team, 2024) and Microsoft Excel was used to create some figures.

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