Hydrology Research

British Hydrological Society

IWA PUBLISHING

Hydrology Research Vol 00 No 0, 1 doi: 10.2166/nh.2021.041

Impacts of climate change on environmental flows in West Africa's Upper Niger Basin and the Inner Niger Delta

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ABSTRACT

Modified water regimes due to climate change are likely to be a major cause of freshwater ecosystem alteration. General Circulation Model (GCM)-related uncertainty in environmental flows at 12 gauging stations in the Upper Niger Basin and flooding within the Inner Niger Delta is assessed using the Ecological Risk due to the Flow Alteration method and a hydrological model forced with projections from 12 GCM groups for RCP 4.5 in the 2050s and 2080s. Risk varies between GCM groups and stations. It increases into the future and is larger for changes in low flows compared to high flows. For the ensemble mean, a small minority of GCM groups projects no risk for high flows in the 2050s (low risk otherwise). This reverses for the 2080s. For low flows, no risk is limited to three stations in the 2050s and one station in the 2080s, the other experience either low or medium risk. There is greater consistency in the risk of change in flood extent, especially in the dry season (medium risk for all groups and the ensemble mean). Some (low or medium) risk of change in peak annual inundation is projected for most groups. Changing flood patterns have implications for wetland ecology and ecosystem services.

Key words: climate change, environmental flows, Inner Niger Delta

HIGHLIGHTS

- Projected river discharge in the Upper Niger for 12 GCM groups is combined with the Ecological Risk due to Flow Alteration (ERFA) environmental flow method.
- ERFA is also applied to projected flood extent within the Inner Niger Delta.
- Risk of river flow change varies between GCM groups and stations. It increases into the future and is larger for low flows than high flows.
- Risk for flood extent is more consistent especially in the dry season (medium risk).

INTRODUCTION

Hydrological conditions within rivers exert critical controls upon aquatic ecosystems. This influence is implicit within the natural flow paradigm (Poff *et al.* 1997) that recognises that a river's regime, characterised by variability, magnitude, frequency, duration, timing and rate of change of discharge, is central to sustaining ecosystem integrity. All elements of the flow regime influence some aspect of riverine ecosystems. Discharge variability, for example, drives fish communities both directly (e.g. influencing migration, spawning and recruitment) and indirectly (e.g. impacting availability and diversity of habitat; e.g. Nestler *et al.* 2012). Indirect influences include the important role of high flows in controlling connections between rivers, floodplains and riparian wetlands. In turn, the resulting wetland hydrological conditions, particularly water-level/inundation regimes, are a dominant influence upon vegetation, animals and biochemical processes that support numerous ecosystem services (e.g. Baker *et al.* 2009). For example, Africa's floodplains are sustained by seasonal floods that underpin agriculture, grazing and fisheries, provide water for direct abstraction or groundwater recharge and sustain habitats contributing to internationally important biodiversity (e.g. Adams 1992). Modifications to river regimes and floodplain inundation can therefore potentially impact wetland ecosystem service delivery (Acreman *et al.* 2014).

Climate change-induced modifications to precipitation and evapotranspiration will alter runoff and river flows (e.g. IPCC 2014). Aquatic ecosystems, many of which have already been modified through human action (Tickner *et al.* 2020), may

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experience additional stress as a result. Changes in flows of water into, within and out of wetlands have the potential to impact inundation patterns and water-level regimes with consequent modifications to wetland hydroecological conditions (e.g. Xi *et al.* 2020). Hydrological models can be used to assess climate change-driven modifications to river flows and wetland water-level or flood regimes by forcing meteorological inputs with General Circulation Model (GCM)-derived climate projections. This process is associated with multiple uncertainties (the 'cascade of uncertainty'; Wilby & Dessai 2010), of which the choice of GCM is often particularly significant. Different GCMs produce variable projections of future climate and, in turn, hydrological responses for the same scenario (e.g. Gosling *et al.* 2011).

Uncertainty is amplified by difficulties in translating projected hydrological conditions to ecological responses. Environmental water science has developed in response to the need to determine flow- and water-level regimes required to maintain ecosystem services and to assess potential impacts of change in hydrological conditions on ecosystems (Dyson *et al.* 2003; Horne *et al.* 2017). A range of environmental flow methods have been developed (Acreman & Dunbar 2004). Many employ the natural flow paradigm and are designed to establish responses of freshwater ecosystems to change, including defining hydrological thresholds beyond which ecological change may be significant (Poff *et al.* 2010). These purely hydrological methods can be considered implicitly holistic (Acreman & Dunbar 2004); if the flow regime is close to natural, the river ecosystem is supported. Conversely, if the regime changes, there is potential for ecological impacts.

This study demonstrates the application of Ecological Risk due to Flow Alteration (ERFA), an environmental flow method developed by Laizé *et al.* (2014) and modified by Thompson *et al.* (2014) and Laize & Thompson (2019). It employs simulated river flows at 12 gauging stations within West Africa's Upper Niger Basin provided by a semi-distributed conceptual hydrological model forced with projections derived from a large ensemble of GCMs. While the hydrological impacts of these projections are detailed by Thompson *et al.* (2017), to the authors' knowledge this is one of the first studies to employ an environmental flow approach to assess basin-wide risk of change for a major West African river system for a large ensemble of climate change scenarios. The study develops approaches to summarise ERFA results for this ensemble, which include both overall assessments of risk of change and the underlying metrics upon which these assessments are made. The novelty of the study is further extended by applying ERFA to projections of flood extent within the Inner Niger Delta, the region's largest floodplain.

The Upper Niger Basin and the Inner Niger Delta

The Inner Niger Delta (Figure 1) lies at the downstream end of a 276,000 km^2 catchment and is fed by the Niger and its major tributary the Bani. Precipitation is highly seasonal and characterised by large inter-annual variability (e.g. Zwarts *et al.* 2005). While peak rainfall occurs in August, wet season duration and total rainfall decline in a southwest–northeast direction. The mean annual precipitation (1950–2000 derived from the CRU TS 3.0 dataset) in the far west of the basin is around 2,100 mm, and the wet season extends for 8 months (March–October). In the far northeast and over parts of the Inner Delta, rainfall is concentrated between July and September with annual totals averaging around 250 mm. Potential evapotranspiration (PET) varies in the opposite direction from around 2,150 mm in the northeast to 1,800 mm in the southwest (Thompson *et al.* 2016).

Upstream and to the west of the Inner Delta, seasonal rains trigger rising river flows normally peaking in September/October before declining to their lowest between March/May (Zwarts *et al.* 2005; Supplementary Figure S1). For example, the mean (1950–2000) seasonal September peak of the Niger immediately upstream of the Delta at Ke-Macina (see Figure 1 for location) is 4,415 m^3 s^{-1}, while by May discharges decline by nearly two orders of magnitude to an average of only 48 m^3 s^{-1}. Similar seasonality is evident for the Bani with the peak (October) and low (May) mean monthly discharges at Beney-Kegny, just before the river enters the Delta, equalling 1,616 and 17 m^3 s^{-1}, respectively. Discharges vary inter-annually and a dominant declining trend has been reported since the 1970s (e.g. Louvet *et al.* 2011). The slow passage of water through the Delta due to low gradients, and the complex drainage system means that seasonal peak discharges downstream occur in November/December (e.g. John *et al.* 1993; Supplementary Figure S1). Evaporation from extensive inundation combined with seepage reduces downstream discharges and overall annual flow volumes. For example, the mean peak (November) discharge at Dire, downstream of the Delta, is 1,935 m^3 s^{-1} compared to the nearly 6,000 m^3 s^{-1} of the combined peaks in the Niger and Bani upstream of the Delta. The magnitude of these differences increases during periods of high flow when inundation extent within the Delta is particularly large (Mahé *et al.* 2009, 2011). While this evaporation may be considered a loss to the Niger system, it may generate rainfall in adjacent catchments (Taylor & Lebel 1998).

Within the Inner Niger Delta, flood extent typically peaks in October/November (Supplementary Figure S1). The area inundated at this time varies from year to year with estimates ranging from 8,000 km^2 in the 1980s to over 24,000 km^2 in the 1950s (see, for example, Mariko *et al.* 2003; Mariko 2004). The lowest water levels within the Delta occur between

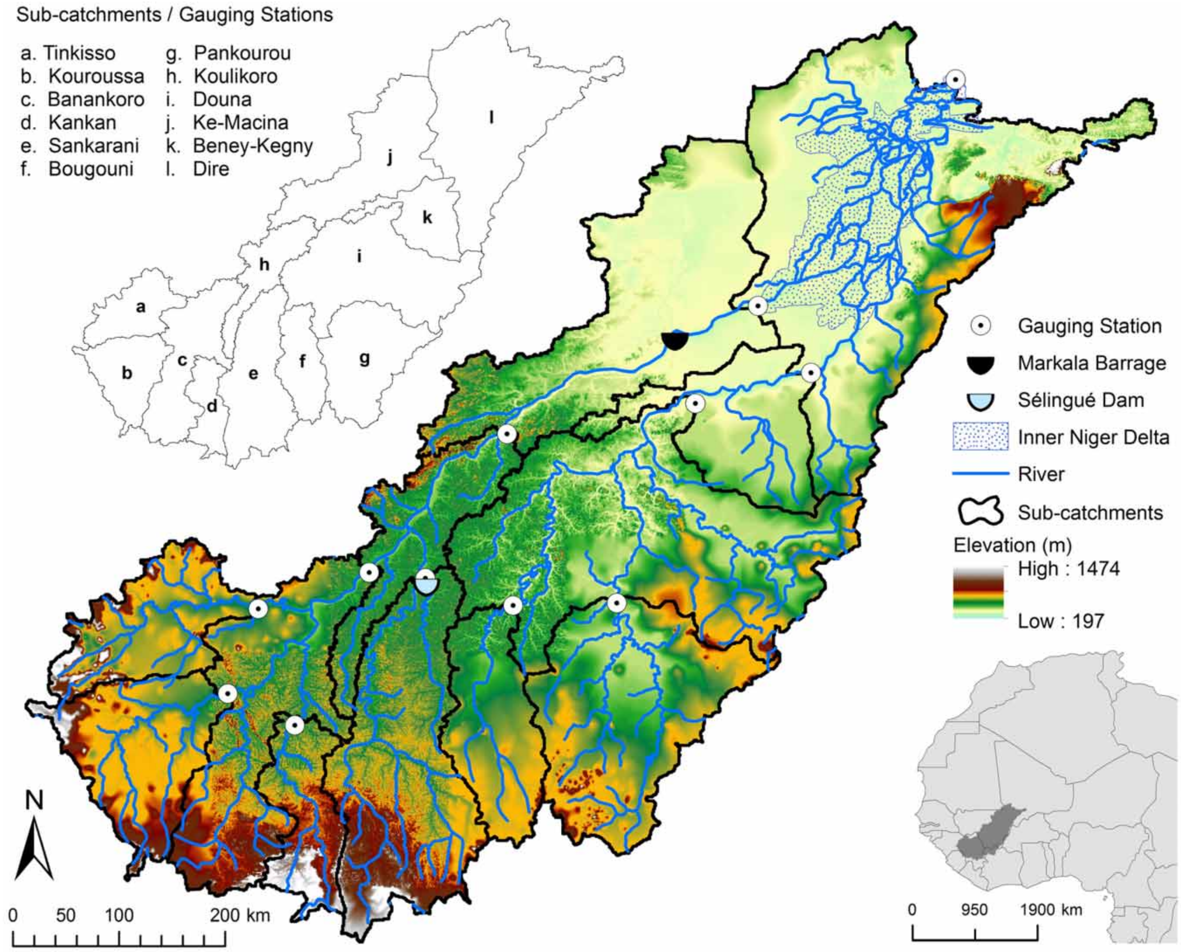

Figure 1 | The Upper Niger Basin and the Inner Niger Delta. The sub-catchments used within the semi-distributed hydrological model and gauging stations for which river discharge is simulated are indicated.

May and July when the area of standing water is $<4,000$ km^2 and much less in dry years (e.g. Sutcliffe & Parks 1989; Bergé-Nguyen & Crétaux 2015).

Inundation patterns exert major ecological controls within the Inner Niger Delta (Rebelo *et al.* 2013). Water depth, flood extent and their seasonal variations control vegetation zonation (Zwarts *et al.* 2005), while fish recruitment and survival during the dry season are strongly influenced by peak flood extent and the duration of inundation in the preceding wet season (e.g. Welcomme 1986). Floodplain resources are utilised by a human population of over 1.5 million with the annual inundation of the Inner Delta supporting agriculture (especially rice), fishing and livestock grazing (e.g. Liersch *et al.* 2013). The Delta also supports a large wildlife population, most notably waterbirds, and is one of the world's largest Ramsar wetlands (Rebelo *et al.* 2013).

METHODS

Hydrological model of the Upper Niger and the Inner Niger Delta

Thompson *et al.* (2016) provide a detailed account of the semi-distributed, conceptual hydrological model of the Upper Niger and Inner Niger Delta. It is, therefore, briefly summarised herein. The model employed 11 sub-catchments with gauging stations at their outlets (Figure 1). Each sub-catchment model comprised reservoirs for soil, groundwater and channel stores for which monthly water balances were evaluated. Precipitation to each soil store was derived from the CRU TS 3.0 dataset that also provided minimum, mean and maximum temperatures used to calculate Hargreaves PET. Actual evapotranspiration was simulated using these estimates but limited by soil storage. Overland flow was calculated as any excess above calibrated maximum soil storage. Throughflow, percolation and baseflow were simulated using reservoir constants when stores were above specified thresholds. Reservoir constants and thresholds were subject to calibration. River discharge was calculated as a product of channel store and a calibrated reservoir constant. The model incorporated the largest extant water resource schemes (Figure 1); the Sélingué hydropower dam on the Sankarani River (from 1982) and irrigation diversions to the Office du Niger project from the Markala Barrage on the Niger (throughout the simulation). Simulated monthly discharge volumes were distributed evenly through the month for comparison with observed monthly mean discharges acquired from the Global Runoff Data Centre (https://www.bafg.de/GRDC/).

Simulated discharges at Ke-Macina and Beney-Kegny provided inflows to a sub-model simulating the volume of water and, in turn, inundation within the Inner Niger Delta following Sutcliffe & Parks (1989) and Thompson & Hollis (1995). River inflows were supplemented by precipitation evaluated as the product of CRU TS 3.0 monthly precipitation and flood extent established using a calibrated volume/area relationship. The volume of water within the Delta was depleted by evapotranspiration, seepage and downstream river flows. The first two of these terms were evaluated as the product of the simulated flood extent and monthly PET (Hargreaves using CRU TS 3.0 data) and a calibrated infiltration rate, respectively. River discharge downstream of the Delta was calculated using the simulated inflows at Ke-Macina and Beney-Kegny and an empirical relationship first established between aggregate observed inflows at these two stations during the four most recent months and observed monthly discharge at Dire. This approach enables revised river outflows to be calculated when changes in inflows occur such as those associated with the climate change scenarios described below (see also Thompson & Hollis 1995). Since simulated discharges at Dire depend upon discharges simulated upstream, calibration of this lowest station was achieved when maximising model performance at the two stations above the Inner Delta. The simulated volume of water within the Inner Delta after each time step was converted to flood extent using the volume/area relationship and the resulting area used in the evaluation of some water balance terms (precipitation, evapotranspiration and seepage) in the next time step. Calibration of the Inner Delta sub-model was achieved via comparisons of simulated peak annual flood extents with estimates provided by Zwarts *et al.* (2005). The latter derive from a relationship established between water levels within the Delta and remote sensing-derived flood extent and are available for each year between 1956 and 2000 (i.e. all but 5 years of the complete model simulation period).

The simulation period extended from 1950 to 2000 and was split (1950–1975 and 1976–2000) for calibration and validation. Performance was also assessed for 1961–1990, and the baseline period used for climate change assessments. The model accurately replicated observed river discharges and peak annual flood extents, especially for the calibration and baseline periods. Performance for river discharge was classed as excellent for most stations and very good for the remainder, while, on average, peak annual flood extents were within 5% of the estimates of Zwarts *et al.* (2005) (Supplementary Table S1, Table S2 and Figure S2).

Climate change scenarios

This study benefits from access to hydrological model results for a set of climate change scenarios previously detailed by Thompson *et al.* (2017). These are based on the Representative Concentration Pathway (RCP) 4.5 scenario simulated by 41 Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs (Supplementary Table S3). RCP 4.5 was originally selected as an intermediate/mid-range emissions scenario (van Vuuren *et al.* 2011). While it is an optimistic scenario based on plans to address current greenhouse gas emission rates (e.g. IPCC 2014; UNFCCC 2015), it has been widely used in catchment/wetland climate change impact studies employing similar approaches (e.g. Yan *et al.* 2015; Ho *et al.* 2016; Robinson 2018; Hudson & Thompson 2019; Rahman *et al.* 2020). The application of RCP 4.5 scenarios to the Upper Niger was designed to expand the geographical range of these assessments.

Thompson *et al.* (2017) described the development of two sets of climate change scenarios. The first employed all 41 GCMs of CMIP5 with monthly delta factors being used to define precipitation and PET for each sub-catchment for two future time slices: 2041–2070 ('2050s') and 2071–2100 ('2080s'). An additional ensemble mean scenario was established using the mean sub-catchment delta factors from all 41 GCMs. While this ensemble mean should serve as a better indicator of climate change than a single GCM (Ho *et al.* 2016), for this to be strictly valid GCMs of the ensemble should be independent of one another (e.g. Pirtle *et al.* 2010). However, GCMs share literature, parameter values and some model code (Abramowitz 2010), and the CMIP5 ensemble includes more than one version of some GCMs or multiple GCMs from a single institution. The second set of climate change scenarios developed by Thompson *et al.* (2017) addressed this potential bias associated with the lack of GCM independence by grouping the 41 GCMs according to their genealogy using 12 groups defined by Ho *et al.* (2016)

(Supplementary Table S3). Delta factors derived from the mean climate projections of the GCMs in each group were used to establish GCM group scenario precipitation and PET for each sub-catchment for the 2050s and 2080s. A group ensemble mean scenario was based on the mean delta factors across the 12 groups. Thompson *et al.* (2017) demonstrated only very subtle differences in the range of projected changes in precipitation and PET, and in turn simulated river discharge and flood extent, between the complete 41 GCMs and the 12 genealogical GCM groups. Similarly, differences between the results for the ensemble mean and group ensemble mean were very small. Given this, and to avoid the potential for biases associated with shared GCM genealogies, this study employs the 12 GCM groups and their ensemble mean (referred to herein as the ensemble mean), thereby replicating the approach adopted by Hudson & Thompson (2019). The two dams included within the model were simulated as being operational throughout the baseline and scenario periods, so that baseline–scenario differences in river discharges and flood extent were due to changes in precipitation and PET alone.

Environmental flows and flooding

The risks of ecological change associated with scenario river flows at each of the 12 gauging stations represented within the hydrological model and flooding within the Inner Niger Delta were assessed using a modified version of the ERFA screening method (Laizé *et al.* 2014). ERFA is based conceptually on the Range of Variability Approach (RVA) which uses Indicators of Hydrological Alteration (IHA) to compare natural and altered flow regimes (e.g. Richter *et al.* 1996). The RVA assumes that organisms or communities exploit all niches created by the complex interactions of hydrology with the landscape. Ecological modifications are more likely as the hydrological regime departs further from the baseline. Risk of ecological change can result from either an increase or decrease in a regime characteristic and risk will consequentially progress from none through low and medium to high as more flow modification thresholds are exceeded. These thresholds are associated with flow regime characteristics that can be indexed by IHAs. While the focus of RVA/IHA approaches has been river flow, with some applications in Africa (McClain *et al.* 2014; Martínez-Capel *et al.* 2017), they are potentially of equal value for wetlands using time series of water-level or flood extent that exert similar ecological controls upon aquatic systems (e.g. Baker *et al.* 2009).

ERFA, as adopted in this study, uses monthly variables (Monthly Flow Regime Indicators; MFRIs), reflecting the hydrological model's time step, to describe baseline and scenario flow and flood regimes. A monthly time step is considered appropriate to capture the primary characteristics of the hydrological regime in large catchments. The selection of these MFRI followed an initial redundancy analysis undertaken by Laizé *et al.* (2014), which led to a reduction from the original 32 RVA IHAs to 16 MFRIs. These were used in European-wide assessments of the impacts of climate change. There are a large number of indices that can characterise a river's hydrological regime and the most appropriate for a given situation depends upon the type of flow regime (Olden & Poff 2003; Monk *et al.* 2007). Accordingly, Thompson *et al.* (2014) further modified ERFA in their climate change assessment for Southeast Asia's Mekong River Basin through the removal of MFRIs associated with European seasons resulting in eight MFRIs. As part of the TEFRIC (Translating Environmental Flow Research in Cambodia; Thompson *et al.* 2018) Project, a series of workshops involving international experts in aquatic ecology, fisheries and water/wetland-related ecosystem services refined ERFA and included two new MFRIs. These 10 MFRIs, which reflect both high- and low-flow (flood extent) conditions (Table 1), have been incorporated within open-access code that undertakes all ERFA calculations (Laize & Thompson 2019). This code and consequently the 10 MFRIs are used in this study. The use of these MFRIs is consistent with the strategy of Olden & Poff (2003), given the dominance of highly seasonal river flows in both the Upper Niger and Mekong basins.

ERFA calculates hydrological variables for each hydrological year of a simulation period. MFRIs then capture the magnitude and variability of each variable as a single value for the complete period. Magnitude is described by the median (50th percentile) and variability by the interquartile range (IQR, difference between 25th and 75th percentiles) of the annual variables. Indicators associated with timing of peak and low flows/flood extents are defined by the months (1–12), in which the largest and lowest flows/flood extents occur and are summarised by their mode. The 10 MFRIs employed in this study were derived from six hydrological variables (Table 1): four medians, four IQRs and two modes. The first five MFRIs characterise high flows (flood extent when applied to modelled times series of inundation within the Inner Niger Delta) and the remainder low flows (flood extent). MFRIs were calculated for the baseline and each scenario using simulated river discharges at each gauging station as well as baseline and scenario flood extents within the Inner Niger Delta.

ERFA then calculates the absolute differences between the baseline and the scenarios for each MFRI. MFRIs based on the median and IQR were considered to depart significantly from the baseline if they differed by more than 30%. Substantial changes in mode-based MFRIs were assumed when differences were greater than 1 month. In addition, since it is possible

Table 1 | Monthly flow regime indicators (MFRIs)

Hydrological variables (one per year)	MFRI[a] (one per period)	Flow/flood type	Regime characteristics
Number of months above threshold[b]	Median (HF1) IQR[c] (HF2)	High	Magnitude; frequency
Month of maximum flow/flood extent (1–12)	Mode (HF3)	High	Timing
Maximum flow/flooding extent	Median (HF4) IQR (HF5)	High	Magnitude; frequency
Number of months below threshold[d]	Median (LF1) IQR (LF2)	Low	Magnitude; frequency
Month of minimum flow/flood extent (1–12)	Mode (LF3)	Low	Timing
Number of periods at least 2-month duration with flow/flood extent below threshold[d]	Median (LF4) IQR (LF5)	Low	Magnitude; frequency; duration

[a] Indicator identification number between brackets.

[b] Threshold: Q5 (95th percentile) from the 1961–1990 baseline period.

[c] Inter-quartile range.

[d] Threshold: Q95 (5th percentile) from the 1961–1990 baseline period.

for there to be multiple modes in either the baseline or scenario time series, the approach adopted in the ERFA code of Laize & Thompson (2019) is employed with significant changes being assumed if the number of modes increases or decreases. The thresholds used in this study are based on expert knowledge established through a series of environmental flow projects and other initiatives (Acreman *et al.* 2008; Laizé *et al.* 2014) as well as the TEFRIC expert workshops (Thompson *et al.* 2018). They reflect the fact that riverine systems have some amount of resilience and that that some river organisms can be highly resilient to flow alterations by either resisting or adapting to their effects or recovering rapidly from them (e.g. van Looy *et al.* 2019). A risk of ecological change classification was used to aggregate ERFA results for each scenario. Classification was based on how many MFRIs differed from the baseline by more than the assigned thresholds (Laizé *et al.* 2014). Risks of ecological change were evaluated for both high and low flows (flood extent) using the coding scheme originally employed by Thompson *et al.* (2014) and now incorporated within Laize & Thompson (2019). In both cases, no-risk, low-risk, medium-risk and high-risk classes were defined when the number of indicators differing from the baseline was 0 (no risk), 1 (low), 2–3 (medium) and 4–5 (high), respectively.

RESULTS

Scenario climate, river flow and flood extent

The hydrometeorological impacts of each GCM group (as well as the original 41 GCMs) for both the 2050s and 2080s are detailed by Thompson *et al.* (2017) and are briefly reviewed here to provide context for the ERFA results. Increases and decreases in mean annual precipitation are projected by different GCM groups and over different sub-catchments (Supplementary Figure S3). Of the 144 sub-catchment–GCM group combinations (12 sub-catchments × 12 GCM groups), annual precipitation increases in 71 (49.3%) and 75 (52.1%) for the 2050s and 2080s, respectively. Across the 12 sub-catchments, the inter-GCM group range of change for the 2050s varies from 18.5% (−11.0 to 7.3%) to 60.0% (−14.0 to 46.0%). The corresponding figures for the 2080s are 26.9% (−18.2 to 8.7%) and 84.0% (−61.5 to 22.5%). The ensemble mean produces both positive and negative, but relatively small, changes over different sub-catchments (2050s: −3.2 to 3.6%; 2080s: −3.4 to 4.6%). Declines in annual PET (maximum: 4.9%) are limited to a single GCM group (9) in just two sub-catchments (d – Kankan and e – Sankarani) in both time slices. In all other cases, the dominance of increases in minimum, mean and maximum temperatures used in the Hargreaves method drives increases in PET. Inter-GCM group ranges are around a quarter of those for precipitation with the largest projected increases being 8.3% (2050s) and 10.5% (2050s). Increases in annual PET for the ensemble mean vary only slightly between sub-catchments (2050s: 3.0–4.6%; 2080s: 3.8–5.5%).

Both increases and decreases in mean discharge are projected at all gauging stations (Supplementary Figure S4). This is repeated for Q5 and Q95 discharges. In most cases, discharges increase at slightly fewer stations compared to precipitation over corresponding sub-catchments. For example, a consistent 66 (45.8%) of the 144 gauging station–GCM group combination project increases in mean discharge in both the 2050s and 2080s. While the changes for some GCMs are small, most (2050s: 81.3%; 2080s: 88.2%) are larger than the bias of the hydrological model in reproducing mean discharge for the baseline period at the respective gauging station (DV in Supplementary Table S1). Inter-GCM group ranges of change are, in percentage terms, over twice as large as those for precipitation. For the 2050s, these range from 49.3% (−30.1 to 19.2%) to 148.5% (67.0 to 81.5%), and for the 2080s 79.7% (−51.7 to 28.0%) to 194.4% (−85.45 to 109.0%). This variability is evident in the river regimes with some GCM groups projecting a slightly later peak. The ensemble mean produces declines (mean: 7.3 and 8.7% for the 2050s and 2080s, respectively) in mean discharge at all 12 gauging stations. Comparable declines are projected for Q5 and Q95. River regimes for the ensemble mean are similar to the baseline, although there is considerable variability between GCM groups (Supplementary Figure S4).

A substantially larger number of GCMs project declining flood extent within the Inner Niger Delta compared to increases (Supplementary Figure S5). These declines are driven by the dominance of reductions in river inflows combined with elevated PET over the Delta which can offset the impact of relatively small increases in river inflows projected by some GCM groups. In the 2050s, the ensemble mean and all but one GCM group (9) project declines in the majority of the 30 annual peak flood extents. Consequently, the overall mean peak flood extent (in November in most scenarios) declines for 11 GCM groups. For the ensemble mean, the 2,777 km^2 reduction in mean November flood extent represents a 19.5% reduction from the baseline. The equivalent decline for the 2080s is 2,977 km^2 (20.9%), although two additional GCM groups project increases in the majority of annual peaks and the mean seasonal (November) maximum flood extent.

ERFA risks of ecological change for scenario river flows

A challenge of the current study is the presentation of ERFA results due to the large number of climate change scenarios employed and the multiple MFRIs used in the overall assessment of the risk of change. Thompson *et al.* (2014) adopted a relatively parsimonious approach when applying ERFA to the Mekong by summarising for each scenario the spatial distribution of risks of change in high and low flows simulated at different locations by a MIKE SHE/MIKE 11 model. However, this earlier study was limited to seven GCMs and one time slice, and it restricted review of the MFRIs contributing to the overall risks of change. We therefore adopt an alternative and new approach (Figure 2) based on the method included in the code developed by Laize & Thompson (2019). Individual subplots for each gauging station show whether each of the 10 MFRIs exceeds thresholds associated with a significant change. High- and low-flow MFRIs are grouped together and results are shown for each GCM group and the ensemble mean (*E*). Risk of ecological change for high and low flows are also shown using the 'traffic-light' colour-coded scheme employed by Laizé *et al.* (2014) and Thompson *et al.* (2014). Figure 3 summarises for each station through the Upper Niger, and both time slices the proportion of the 12 GCM groups whose projections for high and low flows are placed in each of the four risk classes.

ERFA results demonstrate variability between GCM groups and gauging stations. At individual stations, results for the two time slices are generally similar although they vary in detail. Results for specific MFRIs of particular note include the very small number of GCM groups that project significant changes (i.e. >1 month) in the modal timing of peak flows (HF3) across the 12 gauging stations. In both time slices, there are no significant changes in HF3 for all 12 GCM groups at the same nine gauging stations. At the other three stations, only a small minority of GCM groups (2050s: 1–3; 2080s: 1 or 2) are associated with a significant change with some consistency in the results for the two time slices (e.g. Group 8 at c – Banankoro; Group 12 at h – Koulikoro as well as j – Ke-Macina in the 2080s). In all of these cases, significant changes result from an increase in the number of modes (i.e. the addition of October to the baseline seasonal peak of September). Reducing the threshold for HF3 to 1 month would, as a result of the delayed peak projected by some GCM groups (e.g. Supplementary Figure S4), increase the frequency of significant changes in this MFRI. While three (2050s)/two (2080s) stations would still lack any significant changes, the others would all experience such changes especially those in the downstream part of the basin. For example, in the 2050s, eight and seven GCM groups would project significant changes in HF3 at j – Ke-Macina and k – Beney Kegney, respectively (six groups at both stations in the 2080s). Significant changes (i.e. >1 month) in the modal timing of low flows (LF3) are also relatively rare. In the 2050s, they are restricted to a single, and different, GCM group(s) at just four gauging stations, while in the later time slice two GCM groups project significant changes at two stations and one at three stations. In all but one case significant changes are due to either an advance in the modal month of the lowest flows (i.e. a more rapid recession) or an increase in the number of modes, again due to more rapid declines following the seasonal peaks that are predicted by some GCM groups (e.g. groups 1 and 4). A lower threshold of 1 month would increase the frequency of significant changes in LF3 with, for the 2050s, only one station (h – Koulikoro)

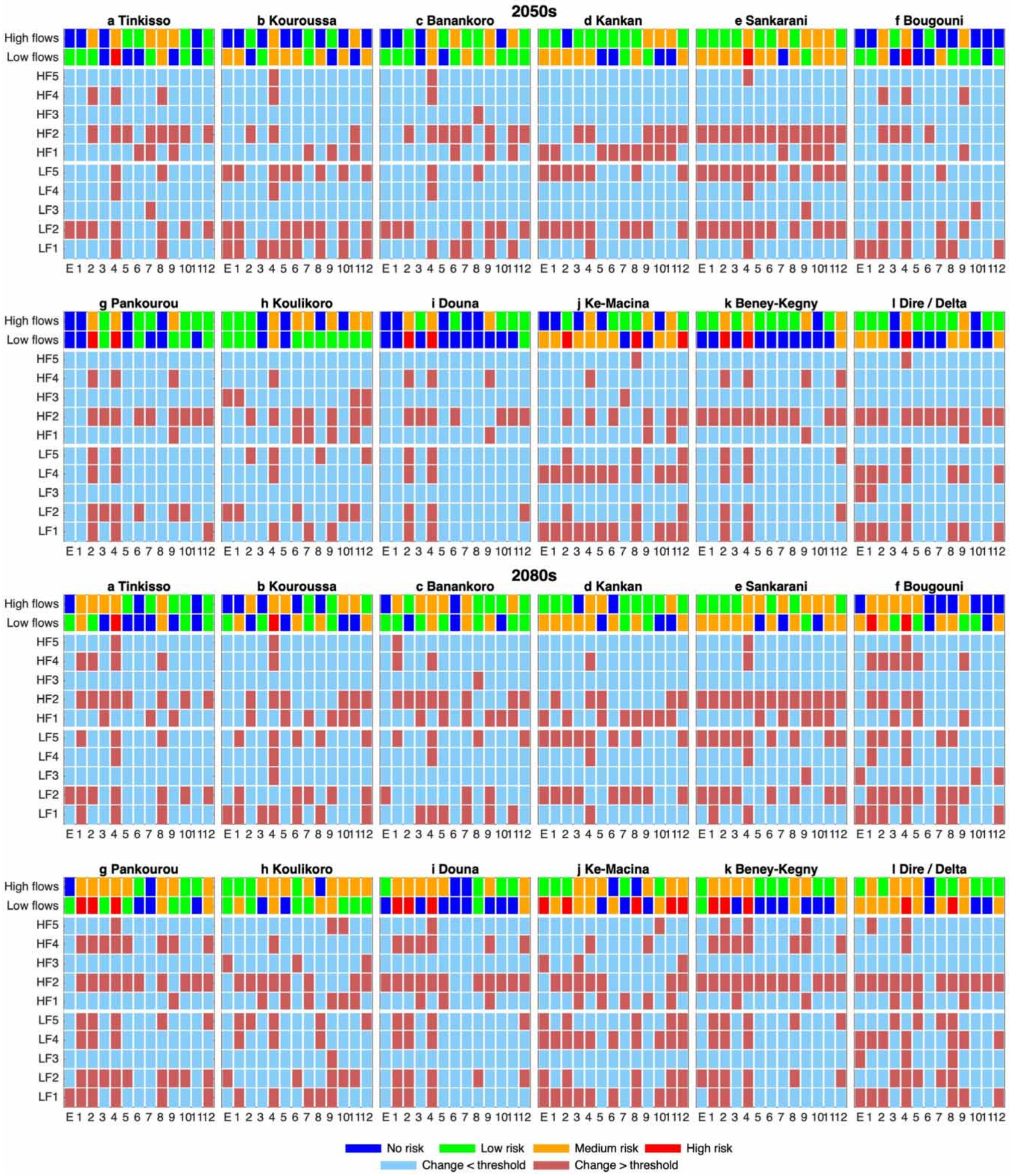

Figure 2 | ERFA environmental flow results for 12 gauging stations in the Upper Niger for the 2050s and 2080s. The lower part of each subplot identifies whether individual high (H)- and low (L)-flow MFRIs are above the thresholds associated with an assumed significant change. The top part of each subplot presents the traffic-light colour-coded classification of risks of ecological change for high and low flows. Results are shown for the ensemble mean (E) and each of the 12 GCM groups.

experiencing no such changes. The number of changes at other stations would range from one to six GCM groups. For the 2080s, significant changes in LF3 would be projected for at least two and up to five GCM groups across the 12 gauging stations. There would, however, be no clear spatial pattern in the distribution of the number of significant changes.

Significant changes in the first two MFRIs associated with the magnitude and variability of high flows (HF1 and HF2) are more numerous compared to the timing of these flows (HF3). For example, at least one GCM group projects a significant

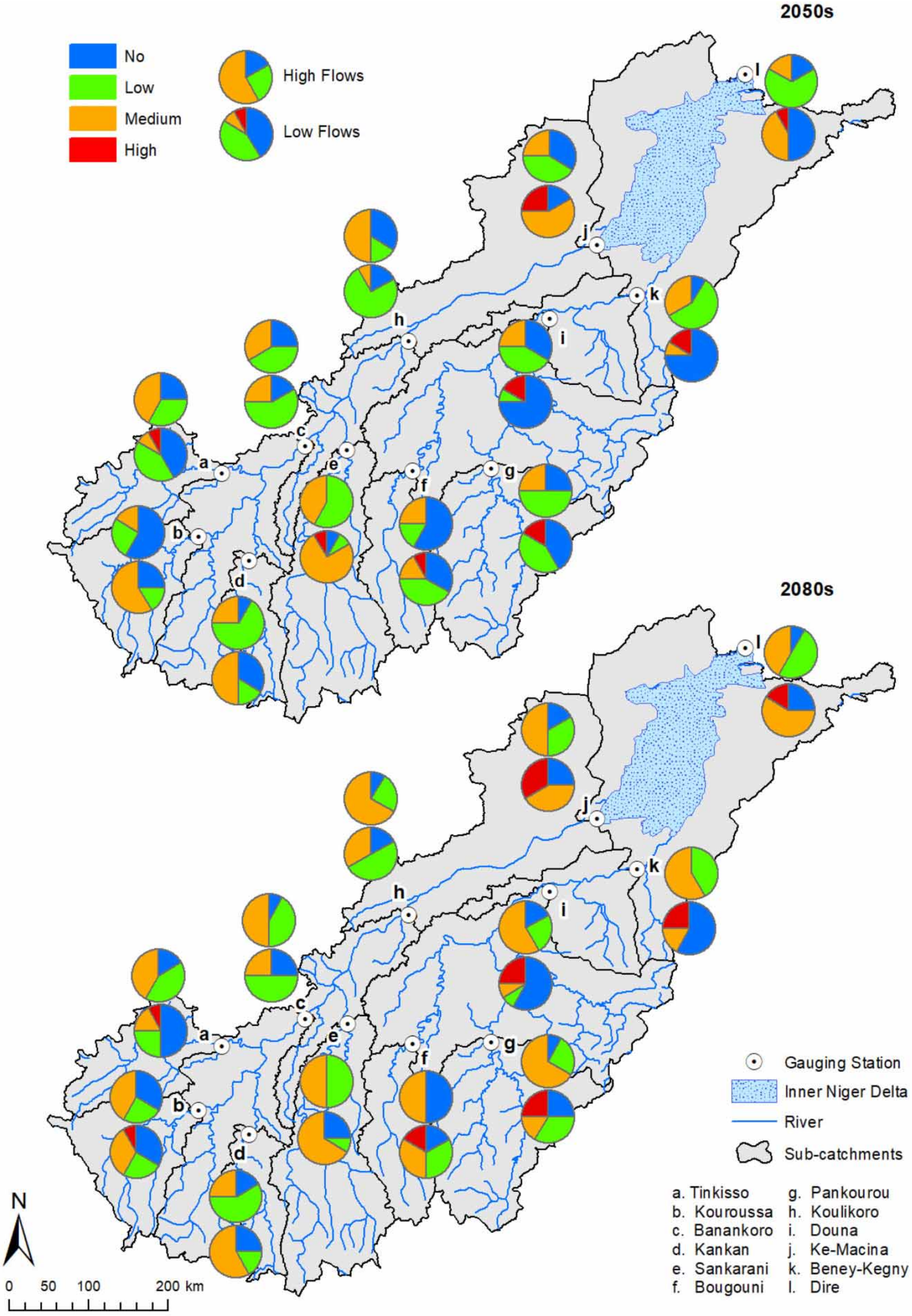

Figure 3 | Distribution of risk of ecological change classes for high and low flows throughout the Upper Niger Basin for the 12 GCM groups for the 2050s (top) and 2080s (bottom).

change in HF1 at every gauging station and across the 12 stations × 12 GCM groups (144 total), significant changes occur in 32 (22.2%) and 50 (34.7%) cases for the 2050s and 2080s, respectively. There is a tendency for a larger number of significant changes to be projected in the upper part of the basin (stations a–e). For example, in the 2050s, the first three of these stations have three significant changes with eight and four being projected for d – Kankan and e – Sankarani. In contrast, no more than two, and in most cases just one, significant change in HF1 is projected for stations that are further downstream (with the exception of h – Koulikoro). In the 2080s, this trend is repeated with at least five significant changes being projected for most of the upper stations (3 for a – Tinkisso), while further downstream most stations experience a smaller number of changes. In all cases, significant changes in HF1 are restricted to some, but not all, of the GCM groups projecting declines in peak (e.g. Q5) and mean discharges as reported by Thompson *et al.* (2016). Significant changes in HF2 are more frequent: 90 (62.5% of the 144 total) and 100 (69.4%) cases for the two time slices, respectively. They are associated with GCM groups projecting both relatively large increases and decreases in Q5 and mean discharges. The significant changes are split almost equally (2050s: 51:49; 2080s: 56:44) between declines and increases in this MFRI (i.e. both reductions and increases in the number of months when scenario discharges exceed the baseline Q5 discharge). A clear and consistent spatial pattern in the distribution of significant changes in HF2 is less discernible although e – Sankarani, in the centre of the basin, stands out as the only station where all GCM groups (and the ensemble mean) project such changes in both time slices, while at k – Beney Kegney and l – Dire, both at the downstream end of the basin, all but two (2050s) and one (2080s) GCM groups (and the ensemble mean) project such changes.

Of the two MFRIs based on the magnitude of the annual peak discharges (i.e. HF4 and HF5), significant changes are more numerous for HF4 (2050s: 20/13.9% of the 144 total; 2080s: 40/27.8%), although there is no clear spatial pattern in their distribution. While significant differences are projected for GCM groups that produce both declines and increases in peak discharges, the former dominate accounting for 80.0 and 72.5% of such changes in the 2050s and 2080s, respectively. Significant changes in HF5 are much rarer (only five and 15 incidences in the 2050s and 2080s, respectively). In the first time slice, they are largely restricted to GCM Group 4, which produces the largest declines in peak and mean discharges throughout the basin (Supplementary Figure S4) and result from decreasing variability in the annual highest flows (i.e. lower median IQR). For the 2080s, significant changes in LF5 are still dominated by GCM Group 4 (eight instances), but others are due to GCM groups that produce both increases and decreases in discharges and the variability in peak flows.

In the 2050s across the 12 stations × 12 GCM groups, there are 49 (34.0%) and 61 (42.5%) significant changes in the first two low-flow MFRIs (LF1 and LF2), which characterise the frequency and variability with which discharges are below baseline Q95 discharges. This increases to 55 (38.2%) and 68 (47.2%) for the 2080s. There is, however, considerable variability between gauging stations (1–10 GCM groups for both MFRIs in the 2050s, 1–9 and 2–9 for LF1 and LF2, respectively, in the 2080s) albeit with no clear and consistent spatial patterns. Significant changes are due to both increases and decreases in these two metrics, although for LF1 changes due to increased dry season flows are more numerous than those due to declines (65:35 for the 2050, 67:33 for the 2080s). Given that LF4 and LF5 are based on periods of at least 2-month durations when discharges are below the baseline Q95 discharge, the numbers of significant changes in these MFRIs are smaller than those for LF1 and LF2. Across the 12 stations × 12 GCM groups, there are 28 (19.4%) and 45 (31.3%) significant changes in LF4 and LF5 for the 2050s. The corresponding figures for the 2080s are 34 (23.6%) and 59 (41.0%). Significant changes in LF4 are almost equally split between increases and decreases in the median number of periods of consistent low flow, while significant changes in LF5 are dominated by reduced variability in the number of these periods (2050s: 97%; 2080s: 93%).

Variable responses of changes in MFRIs produce similar variability in ERFA-derived overall risks of change. For the 2050s, the number of GCM groups projecting no risk of change for high flows at an individual station varies between one (e – Sankarani) and seven (b – Kouroussa and f – Bougouni). The corresponding figures for low flows are one (e – Sankarani) and nine (i – Douna and k – Beney Kegney), respectively. No more than four GCM groups project no risk for both high and low flows at a single station (i – Douna) and at four stations (b, d, e and j); no GCM groups project no risk of change in both extreme flows. Variability in ERFA results is repeated in the 2080s between two (e – Sankarani and k – Beney Kegney) and six (f – Bougouni) GCM groups projecting no risk of change for high flows. Between two (f – Bougouni and h – Koulikoro) and seven (i – Douna) groups project no risks for low flows. The largest number of GCM groups projecting no risk of change in both high and low flows at individual stations is only two (stations a, f and i), while at half of the stations there are no instances of no risk in both extreme flows.

For high flows, low risk is the most frequent class at eight stations in the 2050s (with the number of GCM groups projecting this level of risk ranging between five and eight), reducing to four in the 2080s (range of GCM groups: 5–7). In the 2050s, these stations tend to be slightly more concentrated in the downstream part of the basin (Figure 3). No risk and medium risk each account the most frequent class at two of the remaining four stations in the 2050s. A notable increase in the level of risk is evident for the 2080s with medium risk being the most frequent class at seven stations (no risk at the one remaining station). These include all of the stations in the lower part of the basin with the one exception of l – Dire immediately below the Inner Delta (i.e. stations g–k). The number of GCM groups projecting this level of risk at these stations varies between five and eight. High risk of change in high flows is not projected for any GCM group at any gauging station.

In the 2050s, no risk of change in low flows is dominant at five stations (range in the number of GCM groups projecting this level of risk: 5–9). Of the remaining seven stations, low risk (5–9) and medium risk (6–9) are the most frequent at three and four stations, respectively. Unlike high flows, some GCM groups project high risk of change in low flows. Across the 12 gauging stations and 12 GCM groups, a total of only 13 (9% of the total) high risks of change are projected of which seven are associated with GCM Group 4. At the last three gauging stations above the Inner Delta (i.e. i–k), high risk is the second most frequent risk class albeit with a frequency much lower than the dominant class (either no risk or medium risk). There is no clear and consistent spatial pattern in the distribution of risk classes (Figure 3). In the 2080s, no risk, low risk and medium risk are each most frequent at four stations with similar ranges in the number of GCM groups projecting this level of risk (4–7, 4–6 and 5–8, respectively). Again there is little consistency in the spatial distribution of these risk classes. There is a slightly higher number of incidences of high risk of change (19/13%) across the 144 gauging station–GCM group combinations and again seven are associated with GCM Group 4. As for the 2050s, high risk is the second most frequent risk class at the last three stations above the Inner Delta.

ERFA results for the ensemble mean show different responses for high and low flows as well as a general increase in the levels of risk with the more distant time slice. For high flows in the 2050s, no risk of change is projected for seven of the 12 gauging stations with low risk at the remainder. Results for the 2080s show a reversal of this pattern (no risk: five; low risk: seven). Low risk dominates the results for gauging stations in the downstream part of the basin (h–l for the 2080s). For low flows in the 2050s, three, four and five gauging stations are associated with no, low and medium risk, respectively, with the different risk classes occurring throughout the basin. There is a greater frequency of low risk (six stations) in the 2080s at the expense of no risk (one station) and medium risk (four stations). With four low-flow MFRIs undergoing a significant change, j – Ke-Macina on the Niger upstream of the Inner Delta is projected to experience a high risk of change in low flows.

ERFA risks of ecological change for scenario flood extent

Figure 4 summarises ERFA results for projections of flood extent within the Inner Niger Delta using the same approach as that adopted for river discharge. Changes in low (dry season) flood MFRIs are almost completely consistent across the GCM groups as well as the ensemble mean. In both time slices, all 12 GCM groups, as well as the ensemble mean, project significant changes in LF2 and LF5. In all cases, significant changes are due to declines in the IQR and hence reduced variability of inundation during the low-flood period. No GCM groups project significant changes in LF1 and LF4. Two groups (2 and 4) in the 2050s, which are joined by another group (1) in the 2080s, project a significant change in LF3. These five cases are associated with some of the largest reductions in the wet season flood extent (Supplementary Figure S5) that in turn results in a more rapid draw down over the following wet season. With either two or three MFRIs projected to undergo a significant change, all 12 GCM groups, and the ensemble mean, project medium overall risk of change in the low-flood period.

There is more inter-GCM group uncertainty in ERFA results for the high (wet season)-flood period. In both time slices, only one GCM group (9 – MIROC) projects significant changes in HF1. Two of the three GCMs of this group are outliers responsible for large precipitation increases, especially in the east, some small declines in PET and the largest increases in river flows and flood extent (Thompson *et al.* 2017). Although some GCM groups reduce peak flood extents, the reductions do not exceed the significant change threshold employed by ERFA for HF1. The majority of GCM groups (2050s: 11; 2080s: 10), as well as the ensemble mean, do, however, project significant changes in HF2. In most cases (2050s: nine, 2080s: seven), significant changes in HF2 result from declining variability in the number of months each year when scenario flood extent exceeds the 95th percentile of the baseline flood extent. No GCM groups project a significant change (i.e. >1 month) in the MFRI associated with the timing of peak flood extent (i.e. HF3). However, it is notable that 10 (2050s) and eight (2080s) GCM groups, as well as the ensemble mean in both time slices, would project a significant change if a 1-month threshold was instead used. In all cases, this is due to a delay in the modal month of peak flood extent. In the 2050s, five GCM groups project significant changes in HF4 with two of these groups also projecting changes in HF5. The incidence of significant changes to these MFRIs increases to six and four, respectively, in the 2080s. In all but the significant changes

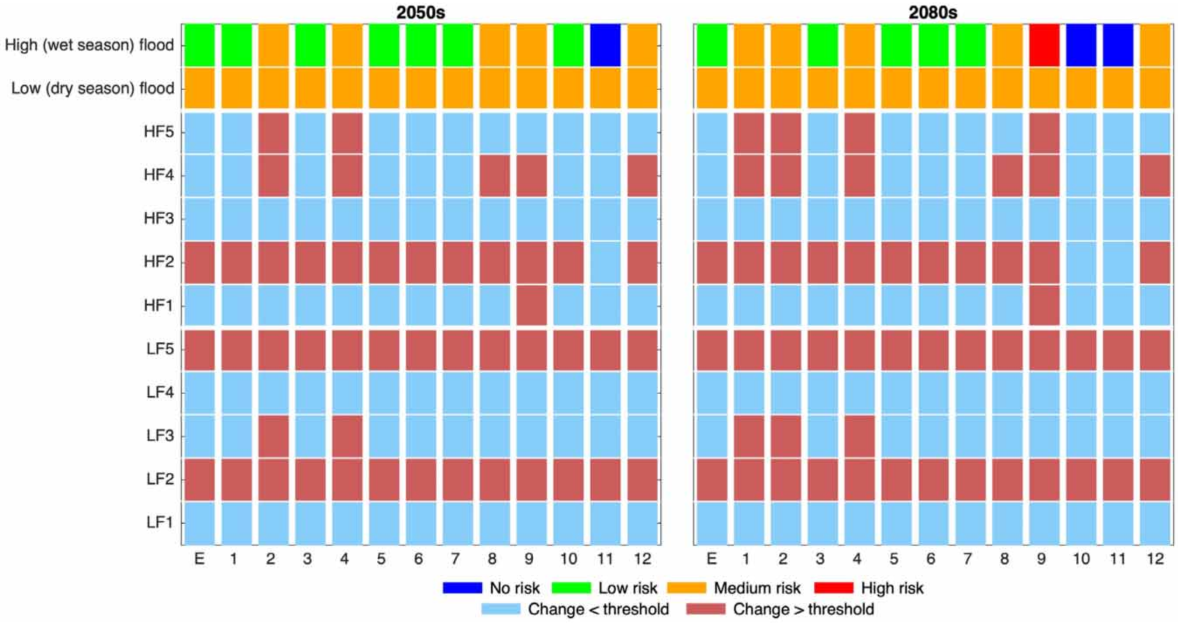

Figure 4 | EFRA results for the risk of ecological change in flood extent within the Inner Niger Delta for the 2050s and 2080s using results from the ensemble mean (E) and the 12 genealogy-based GCM groups.

in HF4 projected by Group 9 in the 2050s and the significant changes in both HF4 and HF5 for this group in the 2080s, these changes are due to reductions in the median annual peak flood extent and the corresponding IQR (i.e. smaller and less variable flood extents). The magnitude of risk of change for the high-flood period ranges for the 2050s from no risk (one group) through low risk (six groups) to medium risk (five groups). While the incidence of no risk increases to two GCM groups (9 and 10) in the 2080s, Group 9 is associated with high risk (low risk: four, medium risk: five). The ensemble mean projects low risk of change to peak floods for both time slices.

DISCUSSION

While many factors influence freshwater ecosystems including light, water temperature, nutrients and species interactions (Moss *et al.* 2009), discharge is considered the key factor within rivers. The dynamic character of a river's natural flow regime is pivotal to biodiversity and ecosystem integrity (Poff *et al.* 1997; Lytle & Poff 2004). It controls nutrient delivery, pollutant dilution and riverine habitat creation (Southwood 1977). Similarly, ecological conditions within wetlands, and in turn the multiple ecosystem services that these environments provide, are fundamentally driven by hydrological characteristics particularly the extent, depth, duration and frequency of inundation (e.g. Baker *et al.* 2009; Maltby *et al.* 2011). Within riverine wetlands, including floodplains, these hydrological conditions are most strongly influenced by the regimes of the rivers with which they are associated (Tockner & Stanford 2002). Flow alterations due to climate change, as well as other factors including water resources management, therefore have the potential to impact riverine, riparian and floodplain habitats, with the modification or loss of ecosystem services (Okruszko *et al.* 2011; Acreman *et al.* 2014; Laizé *et al.* 2017; Xi *et al.* 2020). Depending upon the magnitude of hydrological changes, thresholds may be exceeded beyond which significant ecological alteration occurs (Richter *et al.* 1996; Bunn & Arthington 2002).

The ERFA screening method is designed to enable an initial assessment of the risks of ecological risks of change based on the number of hydrological indicators (i.e. MFRIs) that differ from the baseline beyond specified thresholds (Laize & Thompson 2019). It enables rapid assessments of such risks and is particularly valuable when assessing relatively large numbers of potential future conditions such as the ensemble of climate change scenarios employed in the current study. There is considerable variation in the EFRA-derived risks of ecological change in river flows within the Upper Niger Basin across the 12 GCM groups. This follows widely reported GCM-related uncertainty within the overall 'cascade of uncertainty' in climate change impacts (Wilby & Dessai 2010) for river systems around the world (e.g. Vetter *et al.* 2015; Krysanova *et al.* 2017; Chan *et al.* 2020). As described by Thompson *et al.* (2017), both increases and decreases in river discharge across the Upper Niger of varying magnitude are projected by the different GCM groups. This variability is reflected in the direction of significant changes in some ERFA MFRIs (e.g. HF2 – suggesting increases and decreases in the variability of peak discharges – and both LF1 and LF2 – suggesting increases and decreases in the magnitude and variability of dry season flows). For other MFRIs, there is more consistency in the direction of change. This is most notable for HF1, which is restricted to GCM groups projecting relatively large increases in the highest flows.

With roughly an equal number of GCM groups projecting increases in river discharge as those that project declines, the changes simulated for the ensemble mean are small with relatively few thresholds for significant changes in the ERFA MFRIs being exceeded. This is especially the case for high flows where for the 2050s ERFA projects no risk of change for the ensemble mean at a majority of gauging stations (seven, low risk at the remaining five). In common with other studies (e.g. Jobst *et al.* 2018), the magnitude of changes and hence the risks do increase into the future (i.e. 2050s vs. 2080s), so that for the ensemble mean low risk of change for high flows is projected at seven gauging stations (no risk elsewhere) in the 2080s. There is a concomitant increase in the number of higher risk classes projected for individual GCM groups. Increases in risk into the future is repeated for low flows and, in general, dry season discharges for the ensemble mean are projected to experience more risk of significant change; five and four stations are projected to experience medium risk in the 2050s and 2080s, respectively, while high risk is projected at one station in the 2080s. The relatively larger incidence of risk of change in low flows follows global-scale analyses that have demonstrated much larger increases in the frequency of low-flow conditions compared to changes in high flows (Giuntoli *et al.* 2015).

While ERFA and other RVA/IHA-based approaches (e.g. Richter *et al.* 1996) have been developed for comparing baseline and scenario river discharges, the dominant influence of hydrological conditions upon wetland ecosystems (Baker *et al.* 2009) justifies its application to time series of simulated flood extent within the Inner Niger Delta. There is a consistent medium risk of change in dry season inundation across the 12 GCM groups and the ensemble mean for both time slices. Changes are predominantly due to reduced variability in flood extent at this time of year (i.e. significant changes in LF2 and LF5) rather than the changes in the metrics that define the median magnitude of dry season flood extent (LF1 and LF4). There is more uncertainty for peak floods, although all groups project some degree of risk. Across all groups and both time slices, medium risk is most common although a number of groups project low risk, supporting the previously established larger changes in low-flow conditions (Giuntoli *et al.* 2015). Reduced variability in the extent of inundation is common to many groups (HF2, HF5 for some), while a number experience significant reductions in the annual peak (HF4, although the one group to project high risk is associated with particularly large increases in the peak flood extent). In both time slices, the ensemble mean is associated with low risk due to declining inter-annual variability of peak flood extent.

It is notable that across all GCM groups, there are no significant changes in the timing of high- and low-flood extents (i.e. HF3 and LF3; also repeated in most cases for high and low river flows) using the threshold of significant change in the mode of >1 month. Reducing this threshold to 1 month does increase the number of significant changes in these two MFRIs. The monthly time step of the model, at least in part dictated by the use of mean monthly precipitation and PET derived from the CRU TS 3.0 dataset and subsequently monthly delta factors for the climate change scenarios (see Thompson *et al.* 2016, 2017), means that shorter-term changes in flood extent (and river flow) cannot be assessed by the version of ERFA employed in the current study. However, given the position of the Inner Delta at the downstream end of a large catchment subject to seasonal river flows, inundation is overwhelmingly dominated by the seasonal rise and fall in water levels (e.g. John *et al.* 1993) rather than shorter-term fluctuations which would necessitate smaller model time steps. Moreover, Piniewski *et al.* (2014) demonstrated that while applying RVA/IHA-based approaches at both daily and monthly time steps in a climate change impact study produced subtle changes, the overall assessments of risk of change for a number of GCMs were largely unchanged.

The relative consistency in projected risks of change for the Inner Niger Delta suggests the potential for ecological impacts with socio-economic consequences. Previous studies have highlighted the risk of changing flood patterns to the Delta's wetland habitats and their ecosystem services, notably food production. Inundation area, depth and duration are key controls on these wetlands' ecological functioning and ecosystem services including food production (Liersch *et al.* 2013). Many GCM groups project declining peak flood extents (Thompson *et al.* 2017), although only a subset is associated with significant changes in the ERFA MFRIs that characterise a change in the magnitude of wet season inundation. Such declines could lead to a loss of useable area for floating rice production, enhanced pressure for the conversion of more natural wetland areas and declines in the extent of fish nurseries and rejuvenation of seasonal grasslands that provide fodder for domestic animals and wildlife (e.g. Liersch *et al.* 2019). Conversely, some GCM groups project increases in peak flood extent, although significant changes are restricted to one, and this could enhance flood-related ecosystem service delivery. The majority of GCM groups and the ensemble mean do, however, suggest reduced variability in peak floods. Reduced variability could contribute to a reduction in the inherent risk for communities engaged in floodplain agriculture (e.g. Adams 1992). However, inherent variability in the wet season flood extent may serve valuable ecological functions (Baker *et al.* 2009) and reduced variability, when combined with reductions in flood extent projected by some groups, would concentrate human activities in the same area. This might lead to the over-utilisation of floodplain resources with detrimental impacts on the ecological significance of the floodplain (Zwarts *et al.* 2005).

Zwarts *et al.* (2006) observed that there is frequently insufficient water within the Inner Delta during the dry season to sustain human activities leading to the abandonment of drier parts of the floodplain in recent decades. Reduced variability in dry season flood extent projected by most GCM groups and the ensemble mean would further facilitate the concentration of human activities in more predictable areas each year. Those parts of the floodplain that retain water through the dry season provide vital refugia for fish enabling them to migrate onto the floodplain in the following wet season (e.g. Welcomme 1986). Enhanced exploitation of residual areas of inundation could therefore have profound implications across the Inner Delta. Furthermore, in other African floodplains shifts in flooding patterns, especially in the dry season, have facilitated the invasion of river channels and floodplains by invasive vegetation communities with impacts on native flora and fauna, further modifications to flooding patterns and human use of floodplain resources (Goes 2002; Blaser 2013).

The current study benefits from existing climate change scenario results provided by Thompson *et al.* (2017). These are based on the CMIP5 GCM ensemble and RCP4.5, which is selected as an intermediate/mid-range emissions scenario (van Vuuren *et al.* 2011). Further investigation of risks of ecological change and associated uncertainty could consider alternative emission scenarios (e.g. RCP8.5, which may be associated with larger changes and hence risks of ecological change) or results from the CMIP6 ensemble (Eyring *et al.* 2016). It is also important to recognise other sources of uncertainty and factors that may impact future river flows and, in turn, inundation within Inner Niger Delta. These are reviewed by Thompson *et al.* (2016) and include the land-cover change which has occurred across the Sahel with impacts on river flows (e.g. Amogu *et al.* 2010) and changes in drainage patterns within the Delta associated with channel blockages by vegetation (Goes 2002) or the construction of embankments and slucies (Zwarts *et al.* 2005). Finally, changes to the operation of existing dams and their irrigation schemes, plans for new major water resource schemes within the Upper Niger and unforeseen responses to water management in response to climate change (e.g. Van Dijk *et al.* 2008) represent additional sources of uncertainty. They dictate continual re-evaluation of future river flows and flooding, their ecological consequences and socio-economic impacts.

CONCLUSIONS

This study combines the ERFA environmental flow method with projections of river flow at 12 gauging stations in the Upper Niger Basin. Its novelty includes the application of an environmental flow approach to assess basin-wide risk of change for a major West African river system using a large climate change ensemble. Risks are assessed for two 21st century time slices and the RCP4.5 scenario using 12 GCM groups that collectively contain 41 individual GCMs. Approaches are developed that summarise the overall risk of changes in high and low flows as well as the metrics (MRFIs) upon which these assessments are made. The novelty of the study is extended to include the use of ERFA to assess risks of change in flood extent within the Upper Niger Delta, one of the world's largest Ramsar wetlands.

For river flow ERFA, results show inter-GCM variability in terms of the number of indicators that are projected to change significantly and the resulting overall risks of change. No and low risks of change are more frequent in the 2050s, while the frequency of medium risk increases in the 2080s. High risks of change are infrequent and when they are projected, it is for low flows confirming an overall higher risk of change for dry season discharges compared to those in the wet season.

There is more consistency in the risks of change in flood extent within the Inner Niger Delta, especially for the low, dry season, flood extent (medium risk for all 12 GCM groups and the ensemble mean, while for high flows some groups project low risk). Changes are, in particular associated with reduced variability in the dry season and peak inundation although for some GCMs risk is due to changes in magnitude, predominantly declines, in the wet season flood extent. The dominance of medium risk of change in flooding may potentially induce ecological changes within West Africa's largest floodplain which, given the central role of flooding in ecosystem service delivery, could have socio-economic consequences.

ACKNOWLEDGEMENTS

The current study develops earlier research funded by a grant from the UK Natural Environmental Research Council under the ‘Quantifying and Understanding the Earth System’ (QUEST) programme (NE/E001890/1). The application of the ERFA environmental flow method was undertaken to trial approaches developed under the NERC funded projects ‘Water climate services to inform food and water security in India’ and ‘Translation of Environmental Flow Research in Cambodia’ (TEFRIC; NE/R009325/1).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 19 April 2021; accepted in revised form 27 June 2021. Available online 9 July 2021