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# Increasing Risk of Ecological Change to Major Rivers of the World With Global Warming

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**Key Points:**

- Nine global hydrological models forced by five global climate models provide discharges for 321 major river basins for 1–3°C mean global warming
- An environmental flow method demonstrates increasing risks of ecological change with warming, especially for low flows
- Risks of ecological change vary spatially, with regions most at risk including South America, southern Africa and Australia

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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## Abstract

The hydrological characteristics of a river, including the magnitude and timing of high and low flows, are important determinants of its ecological functioning. Climate change will alter these characteristics, triggering ecological changes in river ecosystems. This study assesses risks of ecological change in 321 major river basins across the globe due to global warming relative to pre-industrial conditions of 1.0, 1.5, 2.0 and 3.0°C. Risks associated with climate-driven changes to high and low flows, relative to baseline (1980–2010; 0.6°C warming), are investigated using simulations from nine global hydrological models forced with climate projections from five global climate models, resulting in an ensemble of 14,445 baseline-scenario members for each warming scenario ($9 \times 5 \times 321$). At the global-scale, the likelihood of high risks of significant ecological change in both high and low flows increase with global warming: across all basins there is a medium-high risk of change in high (low) flows in 21.4% (22.4%) of ensemble members for 1.0°C warming, increasing to 61.5% (63.2%) for 3.0°C. Risks are particularly pronounced for low flows at 3.0°C for many rivers in South America, southern Africa, Australia, southern Europe and central and eastern USA. Results suggest that boreal regions are least likely to see significant ecological change due to modified river flows but this may be partly the result of the exclusion of processes such as permafrost dynamics from most global hydrological models. The study highlights the ecological fragility and spatial heterogeneity of the risks that unmitigated climate change poses to global river ecosystems.

## Plain Language Summary

Ecological conditions within the world's rivers are strongly controlled by the amount, variability and timing of water flowing within them. Climate change will impact river flows with implications for riverine ecosystems. We assess the risks of these ecological changes across the globe. Simulated river flow for 321 major river basins are provided by nine global hydrological models. Their meteorological inputs for 1.0, 1.5, 2.0 and 3.0°C increases in global mean temperature are provided by five global climate models. Simulated river flows are compared with simulations of a recent historical period (1980–2010). Risks of ecological change for 57,780 comparisons of recent versus climate change river flows are assessed using an approach that quantifies changes in high and low flows. We demonstrate increasing incidence of high risks of change in high, and especially, low flows with global warming. Risks are not globally uniform. High latitude northern hemisphere basins experience relatively less risks (potentially underestimated since permafrost loss is not represented in most global hydrological models). Regions where risks are particularly pronounced, especially for low flows, include South America, southern Africa, and Australia. Understanding risks from climate change-induced modifications to river flow is crucial for identifying hotspots and targeting ecosystem conservation efforts.

## 1. Introduction

The hydrological characteristics of a river are key determinants of ecological processes and exert critical controls upon aquatic ecosystems. The links between hydrology and ecosystems are implicit within the natural flow paradigm (Lytle & Poff, 2004; Poff et al., 1997) which recognizes that a river's regime is central to sustaining aquatic biodiversity and ecosystem integrity. The river regime comprises components that characterize the variability, magnitude, frequency, duration, timing and rate of change of discharge. All aspects of a river's regime influence its aquatic ecosystems (Bunn & Arthington, 2002; Richter et al., 1996). The variability in discharge, for example, controls the structure of a river's fish communities directly by triggering life history processes such as migration and spawning, and indirectly by controlling habitat availability and diversity (Nestler et al., 2012; Southwood, 1977). The latter includes the expansion and contraction

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of spawning and nursery habitat, associated with periods of high discharge, and the maintenance of refugia habitats during low discharge conditions. Healthy aquatic ecosystems, in turn, underpin numerous ecosystem services that benefit human communities (e.g., Maltby et al., 2011; Rahman et al., 2020). Modifications to river regimes can therefore alter riverine ecosystems and impact ecosystem service delivery (Acreman et al., 2014; Okruszko et al., 2011; Tickner et al., 2020). Examples of river flow alteration impacts on freshwater ecosystems include those reported by Feld et al. (2014), Lamouroux et al. (2006), Poff and Zimmerman (2010) and Souchon et al. (2008). A range of methods have been developed that are designed to establish the potential impacts of changes in river regimes upon aquatic ecosystems and to determine the required flow regimes to maintain ecologically, economically, and socially important ecosystem services (e.g., Dyson et al., 2003; Horne et al., 2017). Many of these environmental flow methods follow the natural flow paradigm (e.g., Acreman & Dunbar, 2004) and include approaches that define thresholds where modifications to river regimes can be expected to lead to significant ecological change (Poff et al., 2010).

Investigations of how environmental flows and aquatic habitat conditions may be impacted by future climate change has largely been conducted at the basin scale (Ahn et al., 2018; González-Villela et al., 2018; Thompson et al., 2021) or for smaller individual sites (House et al., 2016, 2017; Thompson et al., 2017). Global-scale or even regional studies are comparatively rare (Döll & Zhang, 2010; Laizé et al., 2014; Pastor et al., 2019). Understanding the risks that climate change poses for environmental flows around the globe is, however, crucial for identifying potential future hotspots and for targeting ecosystem conservation efforts (Tickner et al., 2020). Uncertainty in future projections of river discharge means that the identification of basins and regions that, at the global-scale, are of particular concern is challenging. Uncertainty arises from variable projections of the magnitude of future global warming, use of different climate models to project future climate in response to this warming, and the use of different global hydrological models (GHMs) to simulate changes in runoff from the climate projections. Studies have accounted for these uncertainties in projections of runoff and river discharge under climate change scenarios (e.g., Do et al., 2020; Hattermann et al., 2017; Schewe et al., 2014) but to the best of the authors' knowledge the study presented here is the first to assess the implications of climate change on environmental flows by using multiple global climate models (GCMs) with multiple GHMs, under several global warming scenarios. This multi-model approach allows the estimation of the relative risks of ecological changes, and their spatial distribution across the globe, associated with high and low flows from the historical period, under global warming scenarios of 1.0, 1.5, 2.0 and 3.0°C relative to pre-industrial.

## 2. Materials and Methods

The method involves two main steps: (a) obtaining modeled river discharges from different GHMs for a large number of global river basins for both a baseline period and climate scenarios associated with different magnitudes of global mean warming as simulated by different GCMs; and (b) application of an environmental flow approach to assess the potential risk of ecological changes from baseline conditions for each warming scenario across all basins, GHMs and GCMs. Each of these steps is described in the following subsections.

### 2.1. Obtaining Modeled River Discharges for Baseline and Climate Change Scenarios

The analysis uses modeled monthly mean discharges for 321 large river basins distributed across the globe (Figure 1). The basins are a subset of those defined in the DDM30 global river network (Döll & Lehner, 2002) that were co-referenced to the locations of 935 gauging stations held by the Global Runoff Data Centre (GRDC) to facilitate evaluation of GHMs and analyses of their data. The subset analyzed here includes only basins larger than 10,000 km$^2$ so that they are of sufficient size to accommodate the 0.5° × 0.5° output resolution of the models (Hunger & Döll, 2008). All upstream co-referenced GRDC gauged sub-basins were included in each large basin. This generated a final set of 345 basins although 24 were removed because of missing data simulated by one GHM. The basins have a combined area of 65,812 × 10$^3$ km$^2$, approximately 50% of the Earth's land surface (Table 1).

Each basin is classed into one of the eight different hydrobelts defined by Meybeck et al. (2013) (Figure 1). Definition and delineation of these hydrobelts is primarily based upon annual mean temperature and

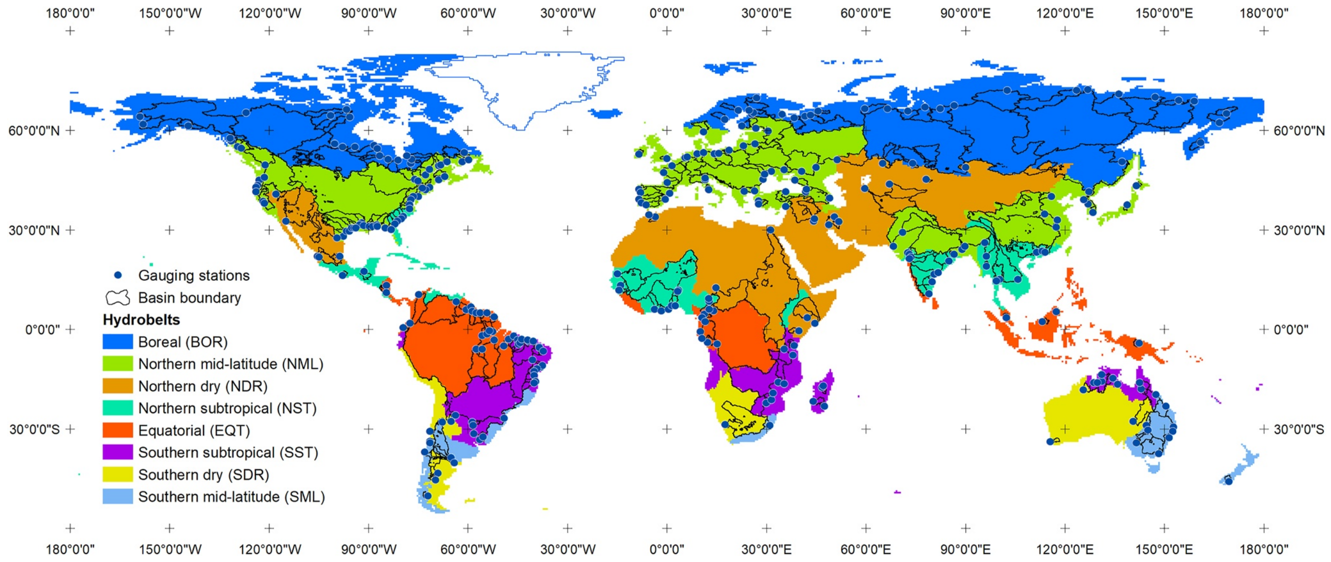

**Figure 1.** The 321 basins used in the analysis and the distribution of the eight hydrobelts established by Meybeck et al. (2013).

runoff as well as, in the case of the mid-latitude, dry and subtropical hydrobelts, location within either the northern or southern hemisphere. In this way basins within a given hydrobelt have similar hydrological and temperature regimes, glacial and postglacial histories and sensitivity to climatic variations. The basins cover between 16% (southern dry) and 71% (equatorial) of the hydrobelts they are located within and in most cases cover at least 50% of the total hydrobelt area (Table 1).

Discharges for each of the 321 basins were obtained from nine GHMs (Table 2). All of the GHMs operate on a 0.5° × 0.5° spatial resolution grid across the global land-surface. The models have different structures, that is, they parameterize the global hydrological cycle in different ways, although some aspects of the models are shared (e.g., the employed potential evapotranspiration schemes; Wartenburger et al., 2018) which reduces some potential inter-GHM uncertainty (Kingston et al., 2009; Thompson, Green, & Kingston, 2014). Water management and other human alterations on the fluvial system are not parameterized, that is, the simulations represent "naturalized" flows, in common with several other climate change impact assessments on future hydrological regimes (Gosling et al., 2017; Prudhomme et al., 2014; Schewe et al., 2014).

The GHM simulations followed the simulation protocol of, and were conducted within, the framework of the Fast Track Phase of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), (Warszawski

**Table 1**
*Distribution and Extent of the Basins Used in the Analysis According to the Hydrobelts Defined by Meybeck et al. (2013)*

| Hydrobelt | Area of hydrobelt ($10^3$ km$^2$) | No of basins in each hydrobelt | Basin area ($10^3$ km$^2$) | Basin area as a proportion of total hydrobelt area (%) |
|---|---|---|---|---|
| Boreal (BOR) | 25,995 | 51 | 16,466 | 63 |
| Northern mid-latitudes (NML) | 24,199 | 102 | 16,899 | 70 |
| Northern dry (NDR) | 30,234 | 24 | 6,685 | 22 |
| Northern sub-tropical (NST) | 10,579 | 37 | 4,451 | 42 |
| Equatorial (EQT) | 16,826 | 35 | 11,946 | 71 |
| Southern sub-tropical (SST) | 10,599 | 46 | 5,895 | 56 |
| Southern dry (SDR) | 8,677 | 11 | 1,354 | 16 |
| Southern mid-latitudes (SML) | 4,008 | 15 | 2,116 | 53 |
| Total | 131,117[a] | 321 | 65,812 | 50 |

[a] Total of non-glaciated land.

**Table 2**
*The Global Hydrological Models (GHMs) Used in the Analysis*

| GHM | Reference |
|---|---|
| DBH | Tang et al. (2007) |
| H08 | Hanasaki et al. (2008a, 2008b) |
| LPJmL | Bondeau et al. (2007), Rost et al. (2008), Schaphoff et al. (2013) |
| Mac-PDM.09 | Gosling and Arnell (2011) |
| MATSIRO | Pokhrel et al. (2012, 2015), Takata et al. (2003) |
| MPI-HM | Hagemann and Dümenil (1997) |
| PCR-GLOBWB | van Beek et al. (2011), Wada et al. (2011, 2014) |
| VIC-Glob-HM | Liang et al. (1994) |
| WMBplus | Wisser et al. (2010) |

et al., 2014). Climate variables required by each GHM were extracted from five global climate model (GCM) simulations (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2 and NorESM1-M) that were forced with greenhouse gas emissions for the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2011) for the period 1971–2099. RCP8.5 was used since it is the only pathway for which projections from all five GCMs reach a 3.0°C increase in global mean temperature relative to pre-industrial by the end of the simulation period (i.e., 2100). The climate variables were bias-corrected towards the Water and Global Change (WATCH) observation-based data set (Weedon et al., 2011) using the approach described by Hempel et al. (2013). This preserves long-term trends in projected temperature and precipitation for climate change impact assessments. Other bias-corrected GCM-GHM projections are available (Frieler et al., 2017) but the total ensemble size (GCM-GHM combinations) in this study is larger, which facilitates a more complete assessment of risk estimation and uncertainty across the globe.

Simulations using each GHM were undertaken using the climate data from each of the GCMs as input (five simulations for each of the nine GHMs). Daily simulated discharges for the 321 basins were extracted from each GHM simulation for 31-year periods centered on the years in which global-mean temperature for each GCM corresponded to four levels of global-mean warming (1.0°C, which approximately corresponds to the present period; and 1.5, 2.0 and 3.0°C) relative to the pre-industrial period. Note that global-mean warming translates into different levels of regional warming across the different hydrobelts and basins. Under the RCP8.5 greenhouse gas emissions scenario from which the four warming levels were computed, regional warming is comparatively higher in the BOR hydrobelts than others, for each GCM, at the end of the century, while precipitation is comparatively higher in the BOR hydrobelts and comparatively lower in the SDR and NDR hydrobelts (Warszawski et al., 2014). The simulated discharges for the 321 basins were originally at a daily time step and were subsequently aggregated to mean monthly discharges to facilitate analysis of changes in long-term trends with global warming and for application of the environmental flow methodology. The identification of global-mean warming levels facilitates a comparison of climate change impacts across multiple and consistent global warming scenarios (note that the central year of the 31-year periods when a global warming level is reached differ between each GCM: for 3.0°C around 2050 for three GCMs and 2075 for the other two). Baseline discharges were extracted from each simulation for the period 1980–2010, representing the historical period (corresponding to 0.6°C above pre-industrial global mean temperature). In this way, 45 (9 GHMs × 5 GCMs) pairs of baseline-scenario discharge time series were generated for each basin for each of the four global-mean warming scenarios (180 pairs for the four warming scenarios). Across the 321 basins this equates to a total ensemble of 57,780 members, where each member is a pair of baseline-scenario discharges. The large ensemble size facilitates the estimation of the likelihood of different levels of risk of change to ecological functioning in response to changing river flows.

### 2.2. Application of the ERFA Environmental Flow Methodology

Potential risks of environmental change for each ensemble member were assessed using a modified version of the Ecological Risk due to Flow Alteration (ERFA) screening method originally described by Laizé

**Table 3**
*Hydrological Variables and Monthly Flow Regime Indicators (MFRI) Used Within the ERFA Environmental Flow Methodology*

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

[a] Threshold: Q5 (95th percentile) from the 1980–2010 baseline period. [b] Threshold: Q95 (5th percentile) from the 1980–2010 baseline period. [c] MFRI identification between brackets. [d] Inter-Quartile Range.

et al. (2014) and since modified by Laizé and Thompson (2019) and Thompson, Laize, et al. (2014, 2018, 2021). The ERFA methodology is based on the Range of Variability Approach (RVA) that utilizes Indicators of Hydrological Alteration (IHA) to compare pre-impact (in this case the baseline) and modified (warming scenario) river flow regimes (Richter et al., 1996, 1997). Application of the RVA/IHA approach is based on the assumption that under baseline conditions some organism or biological community will have exploited all of the ecological niches created by the complexity of the river flow hydrograph and its interactions with the surrounding landscape. In this way, if a river ecosystem is adapted to baseline discharge conditions, changes in river regime have the potential for ecosystem impacts. The risk of these impacts will increase as the modified regime departs further from the baseline and more thresholds of change are exceeded. These thresholds relate to specific river regime characteristics (magnitude, duration, timing, frequency and rate of change) that can be indexed by IHAs (Olden & Poff, 2003). Risk of change will move from none through low and medium to high as more IHA thresholds are exceeded. ERFA was originally designed as a high-level screening tool for investigating large numbers of river sites or basins, or multiple scenarios, to systematically identify potential impacts on riverine ecosystems on which to focus further attention (Laizé et al., 2014).

ERFA was applied to each of the 57,780 ensemble members, that is, the pairs of baseline-scenario discharge time series. Initially ERFA calculates a number of hydrological variables for both the baseline and scenario discharges for each hydrological year of the simulation period (Table 3). The hydrological year is defined automatically as starting in the month with the lowest discharge of the baseline river regime (the mean monthly discharge). The annual series of hydrological variables are used to derive Monthly Flow Regime Indicators (MFRIs, equivalent to IHAs) designed to capture both the magnitude and variability in each variable as a single value for both the baseline and scenario periods. Selection of these MFRIs followed a redundancy analysis undertaken by Laizé et al. (2014) of the IHAs described by Richter et al. (1996, 1997) and subsequent adaptation to reflect the use of monthly time series data (Laizé & Thompson, 2019; Laizé et al., 2014; Thompson, Laize, et al., 2014). The magnitude of each MFRI 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 describing the timing of peak and low flows are defined by the month (1–12) in which the largest and smallest discharges occur and so are summarized by their mode. 10 MFRIs are calculated based on six hydrological variables (Table 3): four medians, four IQRs, and two modes. The 10 ERFA MFRIs are split equally between those that characterize high and low flows.

ERFA calculates the absolute differences between each of the baseline and scenario MFRIs. Following the approach of Thompson, Laize, et al. (2014), significant departures from the baseline for MFRIs based on the median and the IQR are assumed if differences are greater than 30%. In the case of the two mode-based MFRIs a difference larger than one month was assumed to indicate a significant change. These thresholds are based on expert knowledge established through a series of international environmental flow projects and other initiatives (Acreman et al., 2008; Laizé et al., 2014). ERFA aggregates results using a risk of

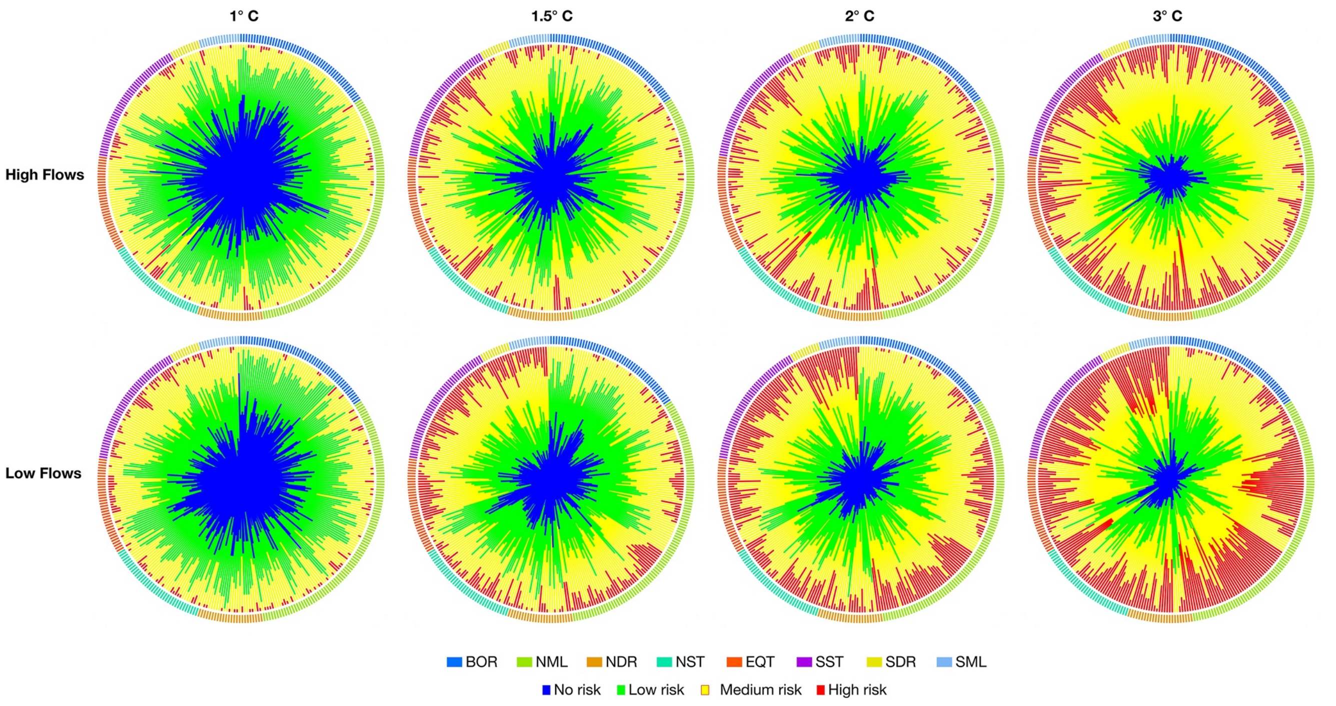

**Figure 2.** Summary of Ecological Risk due to Flow Alteration (ERFA) risk classes for high and low flows for each of the 321 basins and the four warming scenarios. Each subplot shows for each basin the proportion of the 45 (9 GHMs × 5 GCMs) ensemble members placed in the four ERFA risk classes. Basins are grouped by hydrobelt (indicated by the ticks around the circumference of each plot).

ecological change classification that is based on how many MFRIs differ significantly from the baseline. This is undertaken separately for high and low flows with risk classes defined as no risk (a risk score of 0), low risk (1), medium risk (2) and high risk (3) when the number of indicators differing from the baseline is 0, 1, 2–3 or 4–5, respectively. The risk scores (0–3) assigned to each of the four risk classes were, for the purposes of statistical analysis, assigned to each of the 57,780 ensemble members for both high and low flows.

## 3. Results

Figure 2 summarizes the distribution of ERFA risk classes for both high (top) and low (bottom) flows for each of the 321 basins and the four warming scenarios. Basins are grouped by hydrobelt and for each basin the proportion of the 45 ensemble member discharges assigned to each of the four risk classes is shown. In this way, the likelihood from the ensemble of any one particular level of risk for each basin is indicated.

An alternative approach to summarizing ERFA-derived risks of change is based on first cumulating the overall risk scores (i.e., 0–3 for no-high risk) for each basin for both high and flow flows and each of the warming scenarios. These totals are then expressed as a percentage of the possible highest score of 135, that is, if all 45 (9 GHMs × 5 GCMs) ensemble members for a basin were classified as high risk (score 3). This metric is referred to as the "total percentage risk score" and can range from 0 to 100. These results are shown in Figure 3 for both high and low flows. Basins are again grouped by hydrobelt whilst the median scores across the 321 basins for each of the four warming scenarios are also shown.

### 3.1. Risks of Ecological Change for High Flows

Figure 2 demonstrates a clear increase in the risk of change for high flows with increasing warming. Across the 321 basins, on average 40.3% of ensemble members are categorized as no risk of change for high flows under 1.0°C global warming. This figure systematically decreases through 23.3% and 17.5% for 1.5 and 2.0°C, respectively, to 11.0% for 3.0°C warming (Table S1 in Supporting Information S1).

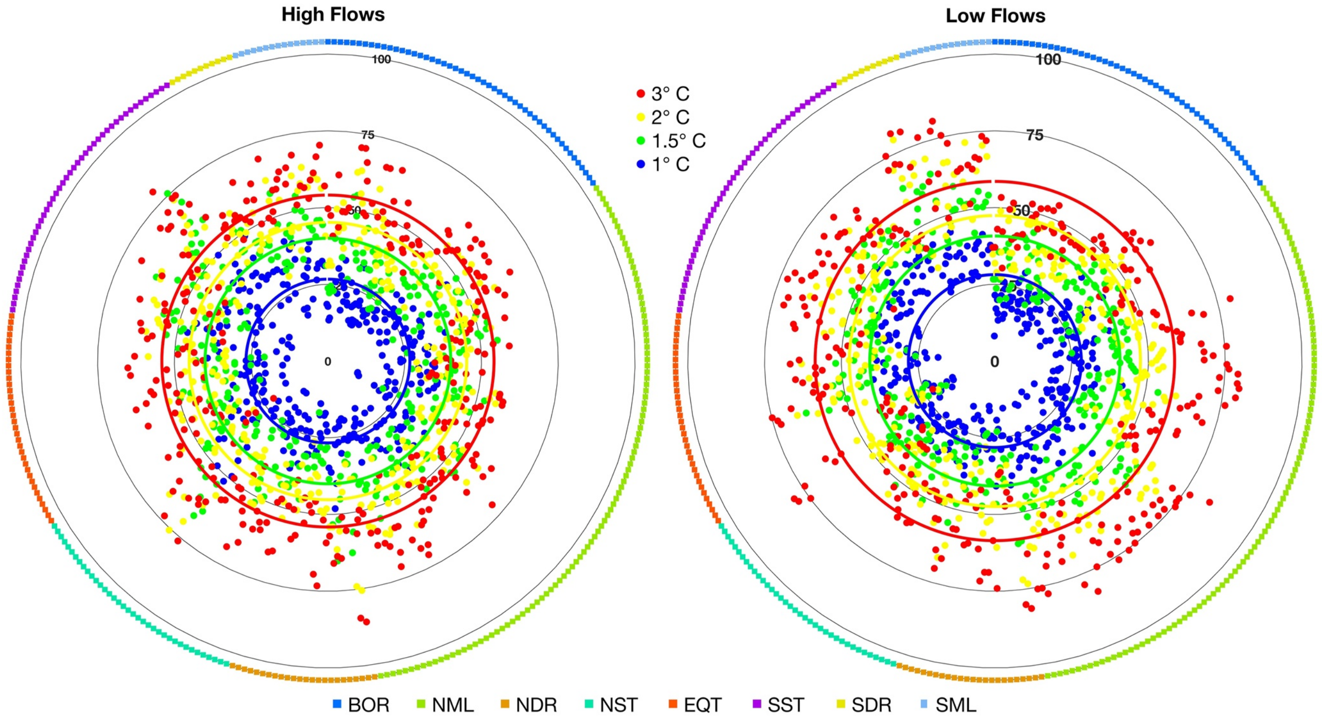

**Figure 3.** Total percentage risk scores derived from ERFA results for high and low flows. This is based on cumulating the overall risk scores for a basin and expressing the result as a percentage of the possible maximum score (135 – i.e., if all 45 (9 GHMs × 5 GCMs) ensemble members were classified as high risk with a score of 3) for each basin and the four warming scenarios. Median scores for each warming scenario across the 321 basins are indicated and basins grouped by hydrobelt (indicated by the dots around the circumference of each plot).

The likelihood of a future where there is a low risk of ecological change linked to high river flows globally declines with increasing global warming; the percentage of ensemble members projecting low risk decreases from 38.2% (1.0°C) to 27.5% (3.0°C). The declines in the number of ensemble members categorized as no/low risk are mirrored by increases for medium and high risk. Whilst on average 20.3% of ensemble members are associated with medium risk of change in high flows for a 1.0°C increase in global mean temperature, a sharp increase to 36.5% is projected for 1.5°C. This increases to 42.8% for 2.0°C whilst for 3.0°C on average nearly half (49.8%) of the ensemble members are associated with this level of risk of change in the highest flows (although there is variability between hydrobelts–discussed below). High risk of change in high flows is rare for a 1.0°C increase in global mean temperature accounting for, on average, only 1.1% of ensemble members across the 321 basins. This increases through 3.8% and 6.3% for 1.5 and 2.0°C, respectively, reaching 11.7% for 3.0°C global warming. The average percentage of the ensemble members with the two highest levels of risk (i.e., medium and high) is 21.4% for 1.0°C and increases through 40.2% and 49.0% (1.5 and 2.0°C, respectively) to 61.5% for 3.0°C.

Increases in the risk of change in high flows with elevated global mean temperature are reflected in the corresponding median values across the 321 basins of the total percentage risk score (Figure 3 and Table S2 in Supporting Information S1). These range from 26.7% for 1.0°C through 40.0% (1.5°C) and 45.2% (2.0°C) to 54.1% for a 3.0°C increase in global mean temperature.

### 3.2. Risks of Ecological Change for Low Flows

Global warming also generally presents an increasing risk of environmental change for low flows across the world's major rivers. These risks are notably larger than those for high flows especially for 2.0 and 3.0°C global warming. Figure 2, for example, shows a considerable expansion in the number of ensemble members for which high risk of change in low flows is projected with progression from 1.5 to 2.0°C and then, in particular, to 3.0°C (although again these changes vary between hydrobelts–discussed below). On average across the 321 basins 20.5% of ensemble members are associated with high risk of change for 3.0°C warming. For 2.0°C this declines to 11.4% whilst the equivalent figures for 1.5 and 1.0°C are 7.0% and 1.9%, respectively (Table S1 in Supporting Information S1).

In contrast, and with the exception of 1.0°C (20.5%), there is a relatively smaller number of ensemble members associated with medium risk of change in low flows although, as for high flows, this increases with the magnitude of warming (31.8%, 37.5% and 42.7% for 1.5, 2.0 and 3.0°C, respectively). As a result, the average number of ensemble members associated with the two highest levels of risk are very similar (differences <2%) to those for high flows (e.g., 22.4% and 63.5% for 1.0 and 3.0°C, respectively compared to 21.4% and 61.5% for high flows).

The frequency of no risk and low risk of change is generally slightly smaller compared to high flows although these differences are no more than 1.1%. Overall, global warming reduces the likelihood of a future where there are no risks of ecological change associated with low flows at the global scale. Across the 321 basins, 39.5% of ensemble members are associated with no risk for a 1.0°C increase in global mean temperature compared to 9.9% for 3.0°C. The corresponding figures for low risk are 38.1% and 26.9%.

Increases in the risk of change in low flows with the magnitude of warming, as well as the higher risks compared to high flows, are reflected in the corresponding median values of the total percentage risk score across the 321 basins (Figure 3 and Table S2 in Supporting Information S1). These range from 29.6% for 1.0°C, through 42.2% and 48.1% for 1.5 and 2.0°C, respectively, to 58.5% for 3.0°C.

### 3.3. Variations in Risks Between Regions

There are notable variations in the risks of change for different hydrobelts that become more apparent with increasing magnitude of global warming. The lowest risks in both high and low flows are dominated by the Boreal (BOR) hydrobelt. For example, the median of the total percentage risk score for low flows across the 51 BOR basins is smaller than the corresponding figures for all of the other seven hydrobelts for each warming scenario. It ranges from 23.7% for 1.0°C, through 34.8% and 41.5% for 1.5 and 2.0°C, respectively, to 48.9% for 3.0°C (Table S2 in Supporting Information S1). The second smallest median total percentage risk scores for low flows are associated with either the EQT (1.0 and 2.0°C) or NST (1.5 and 3.0°C) hydrobelts. Figure 3 shows that in only relatively few BOR basins (in most cases ≤8 (15.7%), 13 (25.5%) for 2.0°C) does the total percentage risk score for low flows exceed the overall median across the 321 basins. If hydrobelts are ranked by the percentage of their basins which have a total percentage risk score for low flows above the 321 basin median (Table S2 in Supporting Information S1), BOR is ranked eighth (NSR seventh) for all warming scenarios. Of the eight hydrobelts, BOR experiences the smallest incidence of high risk for low flows across all of the warming scenarios (Figure 2; ranging between an average across the 51 basins of only 0.5% for 1.0°C to 3.8% for 3.0°C; Table S1 in Supporting Information S1). In contrast, this hydrobelt has the largest incidence of low risk of change for low flows for all warming scenarios except 1.0°C where it instead has the largest incidence (47.5%) of no risk (for the other scenarios either NST (3.0°C) or EQT (1.5 and 2.0°C) has the largest incidence of no risk). Between 46.3% (1.5°C) and 41.2% (3.0°C) of BOR ensemble members are classed as low risk of change for low flows, considerably larger than the means across all hydrobelts (37.2% and 26.9%; Table S1 in Supporting Information S1).

The relatively low risk of change for BOR basins is repeated for high flows, albeit slightly more equivocally. The basins of this hydrobelt have the smallest median high flows total percentage risk scores of all eight hydrobelts for the 1.0 and 1.5°C warming scenarios (20.7% and 34.8%, respectively; Table S2 in Supporting Information S1). For the 2.0°C scenario the corresponding median for the BOR basins is the second smallest after that of EQT (40.7% compared to 40.0%) whilst these two hydrobelts have the joint lowest median total percentage risk score (50.4%) for the 3.0°C scenario. For the 1.0 and 1.5°C scenarios the BOR hydrobelt has the smallest percentage of basins (15.7%/eight basins and 19.6%/10 basins, respectively) in which the high flows total percentage risk score exceeds the overall median across the 321 basins (Table S3 in Supporting Information S1). EQT is ranked second (31.4%/11 basins and 28.6%/10 basins). This pattern reverses for the 2.0 and 3.0°C scenarios with the total percentage risk scores for high flows of 28.6% (10) and 34.3% (12) of EQT basins exceeding the overall median, respectively (37.3%/19 basins for both scenarios in the case of BOR). In all but the 1.0°C scenario, the largest incidence in percentage terms of no risk and low risk of change in high flows is associated exclusively with the ensemble members of the BOR and EQT hydrobelts (ranging from 28.0% and 42.1% for 1.5°C to 13.3% and 32.0% for 3.0°C, Table S1 in Supporting Information S1). Similarly, these two hydrobelts have some of the smallest incidences of high risk of change in high flows. In most cases, the percentage of BOR and EQT ensemble members assigned to this class are half as large as the corresponding values for all 321 basins.

There is some consistency in the hydrobelts that are projected to experience the largest risks of change in high and low flows for the different warming scenarios although the dominance of a single hydrobelt is less equivocal than for low risks of change, especially for high flows. For high flows, the Southern sub-tropical (SST) hydrobelt has the largest median total percentage risk scores for the 1.0 and 1.5°C scenarios (34.1% and 48.5% respectively; Table S2 in Supporting Information S1). The southern mid-latitudes (SML) has the highest median scores for the 2.0°C (56.3%) and 3.0°C (59.3%) scenarios. In all four warming scenarios, the total percentage risk scores for high flows for the majority of SST, SDR and SML basins exceed the corresponding median across the 321 basins (Figure 3). This is especially true for the last of these three hydrobelts where these scores for 12 (80.0%) and 13 (86.7%) of the 15 basins exceed the overall median for the 1.0°C and both 1.5 and 3.0°C scenarios, respectively (Table S3 in Supporting Information S1). These are the largest percentages of all eight hydrobelts. A smaller number of SML basins, but still a majority (10/66.7%), have scores that exceed the overall median for 2.0°C such that this hydrobelt is ranked second after SST (31 or 67.4% of the 46 basins). Either SST (1.0°C and 1.5°C) or SML (2.0 and 3.0°C) have the smallest incidence of both no risk and low risk of change for high flows although, in line with the previously described overall reductions in the frequency of these classes, they decline from 35.2% and 34.5% (1.0°C) to 5.9% and 22.4% (3.0°C) (Figure 2 and Table S1 in Supporting Information S1). SST, SDR and SML are all responsible for at least one of the highest/second highest frequencies of medium and/or high risk although there is variability between warming scenarios and, in some cases, the frequencies of these highest risk classes are larger for other hydrobelts (most notably Northern dry (NDR) which has the highest frequencies of high risk for the 1.0, 2.0 and 3.0°C scenarios).

The highest risks of change in low flows are associated with some of the same hydrobelts that experience large risks of change in high flows. SDR, in particular, has the largest median total percentage risk score for all four scenarios (jointly with SST for 1.0°C). These range from 37.0% (1.0°C) through 56.3% and 66.7% (1.5°C and 2.0°C, respectively) to 71.9% (3.0°C) (Table S2 in Supporting Information S1). In common with the corresponding medians across the 321 basins, these values are larger than those for high flows. The second highest median total percentage risk score for all four scenarios is for SML with values being within 6% of those for SDR (closer still for the less extreme warming scenarios). The majority of SDR and SML (as well as SST and NML) basins have total percentage risk scores for all four warming scenarios that are higher than the corresponding medians for the 321 basins (Figure 3). A consistent 13 (86.7%) SML basins have scores above the overall medians for the 1.5, 2.0 and 3.0°C scenarios (declining to 11 or 73.3% for 1.0°C; Table S3 in Supporting Information S1). Similar consistency is evident for SDR with the scores of 9 (81.8%) basins exceeding the 1.0, 2.0 and 3.0°C medians whilst all of these basins exceed the median for the 1.5°C scenario. Although the majority of SST basins also have total percentage risk scores above those of the 321 basin medians, the percentage of the 46 SST basins with these higher scores declines consistently with warming (e.g., from 89.1% for 1.0°C to 58.7% for 3.0°C). In all warming scenarios except 1.0°C the highest incidence of the high risk class for low flows is associated with SDR followed by SML (Figure 2). Between 16.8% (1.5°C) and 36.8% (3.0°C) of SDR ensemble members are classed as high risk of change for low flows (Table S1 in Supporting Information S1). This is considerably larger than the mean across all hydrobelts (7.0% and 20.5%, respectively). Conversely, SDR ensemble members have the lowest incidence of low risk for all four warming scenarios and no risk for the 1.5°C and 2.0°C scenarios (SST for 1.0°C and NML for 3.0°C).

Within some hydrobelts there are distinctive groups of basins which exhibit different patterns of change in the ERFA-derived risks compared to the rest of the basins of that hydrobelt. The most notable example is a group of six NML basins (located at around four o'clock in Figures 2 and 3) which experience very low risks of change in low flows. Another example, this time for high flows, is a group of four NST basins (at around eight o'clock) which exhibit relatively low risk, especially for 3.0°C. In each of these cases, the basins are located at the boundary with another hydrobelt (Figure S1 in Supporting Information S1) and their ERFA-derived risk more closely follows the patterns in that adjacent hydrobelt. For example, the six NML basins are all located in eastern Canada just to the south of the BOR hydrobelt which, as described above,

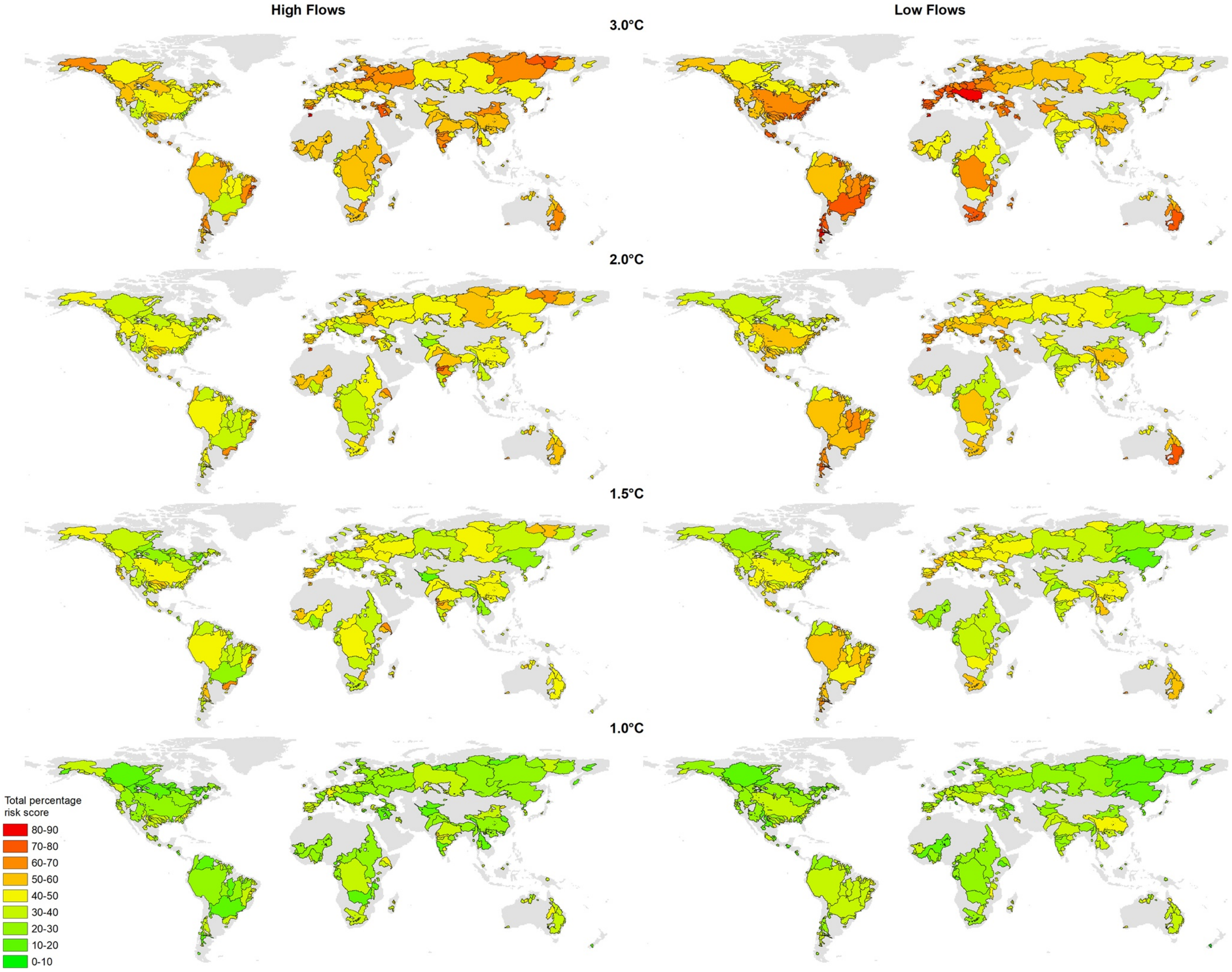

**Figure 4.** Total percentage risk scores derived from Ecological Risk due to Flow Alteration results for high and low flows for each of the 321 basins and the four warming scenarios.

is associated with low risk of change for low (and high) flows. Similarly, the four NST basins are located on the Atlantic coast of the United States and are bordered to the north and west by NML basins with which they share a similar risk profile.

The spatial variations in the ERFA-derived risks of change described above are further illustrated in Figure 4. This shows the total percentage risk score for high and low flows for each of the 321 basins and the four warming scenarios.

Increases in the risk of change in both flow extremes with increasing warming is clearly evident, as is the generally higher risk of change for low flows. Regionally the higher risk for low flows is perhaps most clear for South America which is dominated by the SST, SDR and SMR hydrobelts that are associated with some of the largest risks of change in high and low flows. For example, for 2.0°C warming 38 (67%) of the 57 South American basins have a total percentage risk score for low flows above 50% compared to 19 (33%) for high flows. For 3.0°C warming these figures increase to 54 (95%) and 45 (79%). Basins with relatively high scores, especially for low flows, include the Amazon and Parana, the largest South American basins included in the analysis. Similar patterns are exhibited in other regions of the southern hemisphere including southern Africa and eastern Australia. In the latter, for 2.0°C warming all but one (two) of the 11 basins have total percentage risk scores for high (low) flows that exceed 50% whilst for 3.0°C warming no (only one) basin has a score below 50% for high (low) flows. The Darling River, the largest Australian basin included in the analysis, is notable for having some of the highest scores, including for low flows a value above 50% for 1.5°C warming. Figure 4 also shows that the risk for low flows is significantly greater than for high flows in many Northern mid-latitude (NML) basins, particularly in southern Europe and the central and eastern USA.

At the other extreme, the relatively low risk for basins in the BOR hydrobelt that dominates northern high latitudes is evident. For example, even for 2.0°C warming, the high flow and low flow total percentage risk scores for the northward flowing rivers of Siberia including the Lena, Ob and Yenisey (except for high flows: 51%) as well as North America's Mackenzie and Yukon are less then 50%. Some retain scores below this value for 3.0°C warming although it is notable that for high flows scores for some basins (including the Lena and Yukon) are above 60%.

## 4. Discussion

This study has assessed the risks of ecological change from global warming due to changes in flow regimes for 321 major river basins across the globe. By estimating the likelihood of different levels of risk (no risk, low, medium and high) from a large ensemble of GCM-forced GHM simulations, it has been possible to demonstrate the potential implications for river ecological functioning of changes in high and low flows due to global warming. The risks associated with changes in high and low flows, rather than mean annual flows, were assessed because of the relative significance of changes in runoff extremes with climate change. Globally, low flows are projected to reduce with climate change across a significantly larger area than for declines in mean annual runoff (Döll & Schmied, 2012) while high flows are projected to increase more than mean annual runoff (Arnell & Gosling, 2013). Furthermore, high and low flows are important determinants of aquatic habitat conditions, including temperature and oxygen concentrations, connectivity between habitats including floodplains and compatibility with the life cycle of organisms (Döll & Zhang, 2010; Nestler et al., 2012; Poff & Zimmerman, 2010). These conditions, in turn, influence the provision of riverine ecosystems services (e.g., Okruszko et al., 2011).

The likelihood of any one level of risk occurring (i.e., none, low, medium, high) for a given amount of global warming (1.0, 1.5, 2.0, 3.0°C) is a function of the uncertainties across the different projections from the GCM-GHM combinations. Studies have shown that the dominant determinant of the spread in annual flows and timing is the choice of greenhouse gas emissions scenario or GCM, but for low flows it is the choice of hydrological model (Chegwidden et al., 2019). Thus, the main source of uncertainty in the study is likely to vary between each of the 10 MFRIs that were computed because some of them consider high flows and others low flows. The uncertainty associated with different future greenhouse gas emissions scenarios was largely controlled for by the use of global warming levels but the uncertainties that stem from the GCMs and GHMs respectively were not decomposed. This is because the objective was to estimate the levels of risk according to the full ensemble of model simulations available, that is, all GCM-GHM combinations, rather than explore the risks associated with individual combinations. The risks could be different for specific GCM-GHM combinations but an objective rationale would need to be formulated to justify the estimation of risks from a sub-set of the full ensemble. Model weighting based upon comprehensive evaluation criteria from simulated versus observed climatology (for the GCMs) and hydrology (GHMs) may provide such a rationale but the computation of model weights and model inclusion/exclusion criteria remain issues of critical debate (Zaherpour et al., 2019).

The GHMs have been evaluated in previous studies (Hattermann et al., 2017; Veldkamp et al., 2018; Zaherpour et al., 2018). Although the models show limited ability to replicate the historical timing of the seasonal cycle in northern hydrobelts and the magnitude of the seasonal cycle in southern hydrobelts, they perform better when the model outputs are temporally aggregated to mean annual and extreme runoff indicators (Zaherpour et al., 2018). The limitations of the models are likely to have only a marginal impact on the reliability of the estimates presented in this study because the ERFA MFRIs were derived from annual series of hydrological variables. The ERFA approach itself was explicitly developed as a large-scale screening tool designed to highlight where and under what conditions there is most risk of ecological impact on rivers (Laizé et al., 2014). It is ideally suited for application to large ensembles such as that employed in the current study which derive from multiple GHM-GCM projections. It is not designed as a method to characterize the precise nature of this impact and, indeed, impacts of flow alterations on riverine ecosystems depend on the type of flow being altered, how alteration manifests itself (e.g., high flows affecting floodplain connectivity, low flows influencing dry season refugia) and on different organisms, life stages or ecosystem services (Bragg et al., 2005). Some ecological responses are likely to be the same whether MFRIs increase or decrease (e.g., lower or higher magnitude of high flows or low flows may alter assemblages and reduce diversity; Poff & Zimmerman, 2010) whilst others may vary with the direction of change. By identify the relative risks of change in different regions including, for example, the identification of hotspots, it is possible to then undertake more detailed assessments of the nature of projected changes in river regimes and their implications for individual species and ecosystem services (e.g., Thompson et al., 2021).

The study does not explore the effect of human interventions on basin discharge including, for example, dam operations and water withdrawals. The GHM simulations were conducted for naturalized flows, that is, without such human intervention, as in other climate change impact studies (e.g., Gosling et al., 2017; Hudson & Thompson, 2019; Prudhomme et al., 2014; Schewe et al., 2014; Thompson et al., 2013). However, the additional effect of human interventions provides potential added stressors to river functioning (Tickner et al., 2020; Vörösmarty et al., 2010). Evidence demonstrates that human interventions can aggravate water scarcity and modify flow regimes at the regional (Laizé et al., 2014) and global (Veldkamp et al., 2017) scales. These changes, in turn, affect river ecosystems and their biodiversity (Su et al., 2021). Conversely, in some situations, river regulation might offer opportunities to mitigate the impacts of climate change on river flows (Sundt-Hansen et al., 2018; Wang et al., 2017; Yun et al., 2021), as well as water temperatures (Null et al., 2013). In many cases, this will require modifications to current operation rules and infrastructure (Kingsford, 2011) as well as the development of approaches that enable trade-offs between environmental flows and water resource use (Bair et al., 2019; Singh et al., 2011). Just as the impacts of climate change upon river flows vary globally, the nature and magnitude of human interventions vary from basin to basin, region to region and between different GHMs. The application of the environmental flows approach employed herein to an ensemble of simulations of naturalized and human-impacted conditions respectively (e.g., Zaherpour et al., 2018), would provide a means of exploring this variability. In lieu of such an assessment, the implications of human interventions for the risks estimated in the study can be inferred from other work. Human interventions have not substantially contributed to historical patterns of low, mean and high river flows at the global scale, rather historical trends are attributable to anthropogenic climate change (Gudmundsson et al., 2021). However, the impacts of human interventions have been significant at the basin scale for several large basins in parts of Asia and the western United States, particularly the Colorado and Indus basins, where declines in runoff between 5%–15% have been attributed to human interventions (Haddeland et al., 2014). The implications of this are that the study may be underestimating the total risk to river ecosystems for some basins in Asia and western United States because here the impact of climate change (reduced flows) will add to the impact of significant human interventions (reduced flows from water withdrawals).

For any amount of global warming, the relative contributions of climate change and human interventions to river flow modification and, in turn, risk of river ecological change will vary according to the extent of human interventions in the future. As well as the Colorado and Indus basins, threats to river biodiversity due to human interventions have more broadly been identified for much of Europe (excluding Scandinavia and northern Russia), large parts of central Asia, the Middle East, the Indian subcontinent and eastern China (Vörösmarty et al., 2010) so the relative contribution of climate change to the risks of river ecological change in these regions will be comparatively smaller than for regions where human interventions pose a smaller threat to river biodiversity such as in the BOR hydrobelt and parts of the SST hydrobelt in northern Australia (Vörösmarty et al., 2010). The effects of climate change in the latter two regions may, in practice, be more noticeable than in regions where there is significant human intervention because the changes will be imposed on natural (or near natural) river flow regimes, rather than against a backdrop where the river's regime is managed by humans for water consumption. The relative contributions of climate change and human interventions will be important for the development of adaptation and mitigation strategies that aim to enhance the resilience of river ecosystems to future change.

Ecological risks due to climate-driven changes in river flow were estimated using the ERFA method by comparing hydrological characteristics from a 31-year historical baseline (1980–2010) to the four global warming scenarios. The four warming levels were selected to indicate: present-day risks relative to the historical baseline (1.0°C); the risks that would exist under climate mitigation in line with the 1.5 and 2.0°C goals of the Paris Agreement; and a higher warming scenario (3.0°C). These four warming levels have also been assessed in other recent hydrological climate change impact studies (Jeong et al., 2019; Shrestha et al., 2019, 2020). The baseline period corresponds to 0.6°C above pre-industrial global mean temperature but the world has continued to warm in the past decade. The period 2006–2015 was assessed to be 0.87°C above pre-industrial (Allen et al., 2018) and in 2015 global mean temperature reached 1.0°C relative to pre-industrial (Blunden & Arndt, 2016). The risks presented here for 1.0°C therefore correspond to approximately the present period and to this end provide an insight into how anthropogenic climate change has already imposed a threat to the ecological functioning of global rivers by modifying flows over the past few decades. A full attribution of risks to human influence on the global climate was not the goal of this study, however, as this would require an estimation of risks under both pre-industrial control climate conditions and present climate. Several of the GHMs included in this analysis are currently running a series of multi-centennial pre-industrial river discharge simulations, and present-day simulations as part of ISIMIP3a (www.isimip.org/protocol/#isimip3a). These additional model simulations will provide an opportunity to quantify the extent to which recent changes in environmental flows can be attributed to anthropogenic (as opposed to natural) climate change.

Some regions of the world have experienced significant hydrological drying trends in runoff prior to, and during, the study's baseline period (1980–2010, 0.6°C global warming), particularly some parts of the SDR hydrobelt, including southern Africa and southeastern Australia (Gudmundsson et al., 2021) and the world has continued to warm since the end of the baseline period, to a greater extent in Boreal regions than elsewhere (Allen et al., 2018). Thus the risks estimated in this study underestimate the totality of the effect of climate change, especially in these regions, because anthropogenic global warming has already had an effect on the climate and river flows by the start of the baseline period.

The results of the assessment provide new insights on the threat of climate change to river ecological functioning because it is the first study, to the authors knowledge, to use multiple GCMs with multiple GHMs to quantify the global-scale risk of future changes to the world's rivers based on the concept of environmental flows. Previous assessments have employed a single GHM (Döll & Zhang, 2010; Pastor et al., 2019) whereas nine were applied in the present study. The resultant large ensemble of projections has enabled quantification of the likelihood of different magnitudes of risk. As a result, a key finding of the study is that at the global-scale, the likelihood of seeing a future characterized by a high risk of significant ecological change due to altered river flows increases with the magnitude of global warming. Increasing risks are projected for both high and low flows and are particularly pronounced for low flows at the highest level of warming (3.0°C). The higher risks projected for low flows (compared with high flows) reflect relatively different shifts in river flow regimes with climate change at the global-scale, both in terms of frequency of occurrence and areas affected. An earlier assessment that used the majority of the GHMs employed in the present analysis (and with the same forcing GCMs), showed that global warming under a high emissions scenario (RCP8.5) is projected to increase the frequency of days with low flow conditions considerably more than for high flows: a 16% ensemble mean increase by end of century compared with 7% (Giuntoli et al., 2015). The same study also showed that these changes in frequency affect a significantly larger proportion of the global land surface for low flows than for high flows. The larger changes in low flows (frequency and area) relative to high flows therefore results in the greater risk to river ecosystems for the former at the global-scale as quantified in the current study.

While at the global-scale, increases in risk with magnitude of climate change are evident from this study, regional variability underlies the global picture of change because spatial heterogeneity in the relative changes of high and low flows with global warming determines the spatial variability of risks. The boreal hydrobelt (BOR) presents the lowest risk across all hydrobelts at 3.0°C warming, for both high (jointly with EQT) and low flows, although the risk is not negligible. However, in contrast to the overall global picture where the risks are higher for low flows than for high flows (median total percentage risk scores of 58.5% and 54.1%, respectively for 3.0°C; Table S2 in Supporting Information S1), the risk at the most extreme warming scenario is higher for high flows in boreal regions (median total percentage risk score of 50.4% for high flows compared to 48.9% for low flows) with equal risk (34.8%) in the two flow extremes for 1.5°C. BOR with NST (again for 1.5 and 3.0°C) are the only hydrobelts where the median total percentage risk score is higher for high flows than for low flows. This spatial pattern in risk emerges because under climate change, increases in the duration of high flow conditions will generally be limited to high northern latitudes and northern sub-tropical regions while other global regions see little change (Giuntoli et al., 2015). Furthermore, in the high northern latitudes low flows are considerably less affected by climate change compared with high flows.

The relatively lower risks associated with the BOR hydrobelt compared to other hydrobelts could be an effect of underestimating the risk here because most of the models omit some processes that are important in this hydrobelt. The LPJmL GHM (strictly a dynamic global vegetation model [DGVM]) estimates permafrost dynamics (Schaphoff et al., 2013) and includes active vegetation whereby the vegetation can change in an area in response to $CO_2$ concentration, air temperature, and precipitation, but the other GHMs do not simulate these processes. The effects of melting permafrost with global warming are therefore not considered by the whole model ensemble. Although the GHMs perform well in many Boreal basins (Zaherpour et al., 2018) the evaluation of the models has been based on the historical period when permafrost melting has played a less significant role in determining runoff volumes compared to how it will under global warming scenarios. Over 40% of the present-day permafrost area could be lost globally with 2.0°C global-mean warming (Chadburn et al., 2017) which implies the high flows in the BOR hydrobelt could be greater than estimated under the global warming scenarios considered in this study, and in turn present a greater ecological risk. Re-calculating the total percentage risk score using the results from only the LPJmL GHM, the sole DGVM participating in this study (see Text S1 and Figure S2 in Supporting Information S1), shows that whilst basins in the BOR hydrobelt are often projected to experience relatively low risk of change, this pattern is much more equivocal and, as expected given the overall smaller number of baseline-scenario pairs, inter-hydrobelt differences are smaller. For example, BOR basins have the lowest median total percentage risk scores for high flows for the 1.0°C (20.0%) 1.5°C (33.3%) and 2.0°C (40.0%) scenarios (although for 1.0 and 2.0°C this is jointly with three other hydrobelts; Table S4 in Supporting Information S1). For 3.0°C, BOR is the fourth smallest behind three hydrobelts with the same, slightly lower, (53.3% vs. 46.7%) median. For low flows, the median total percentage risk scores for BOR basins are ranked either lowest (1.5°C, 26.7% jointly with two other hydrobelts), second lowest (3.0°C, 46.7% jointly with two other hydrobelts) or third lowest (1.0°C, 20.0% and 2.5°C, 40.0% with three hydrobelts; Table S4 in Supporting Information S1). LPJmL results also suggest that in most cases risks of change are larger for high flows compared to low flows, the reverse of the pattern obtained using the complete ensemble. This may be due to the representation of interactions between climate and catchment characteristics (i.e., vegetation, permafrost dynamics) within this one GHM, pointing to the need for their inclusion within other models, something which the GHM modeling community is starting to address (Stacke & Hagemann, 2021- in review).

In other hydrobelts, Giuntoli et al. (2015) showed that increases in the frequency of days with low flows are significantly greater than they are for high flows, particularly for the Northern mid-latitude (NML), Southern sub-tropical (SST), Southern dry (SDR) and SML hydrobelts. This explains why the ERFA-derived risks are considerably higher for low flows in these regions than they are for high flows. The EQT hydrobelt shares the lowest level of risk for high flows at 3.0°C with BOR and is projected to experience no change in the frequency of days under high flow conditions (Giuntoli et al., 2015). SST, SDR and SMR feature as three hydrobelts where the incidence of high risk is greatest with global warming, particularly for low flows. This is because globally, some of the most significant changes in low flows are projected for these regions with global warming, including strong declines in the 10-year return period minimum annual runoff (Arnell & Gosling, 2013), an increasing frequency of low flow days (Giuntoli et al., 2015; Prudhomme et al., 2014), and a general decline in terrestrial water storage that disproportionally affects the southern hemisphere (Pokhrel et al., 2021).

Across all 321 basins there is a high risk of change in high (low) flows in only 1% (2%) of ensemble members at 1.0°C but this increases to 12% (21%) at 3.0°C. If medium and high risk classes are combined then there is a risk of significant ecological change associated with high flows for 62% of ensemble members, and 63% for low flows. This level of likelihood can be interpreted as "more likely than not" (>50%–100%) according to the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010). The term "more likely than not" highlights that the results presented here are inherently uncertain. This is due to variability in the projections of future climate from the different GCMs and different simulations of river discharge between the GHMs. However, the level of likelihood (>60%) for medium-high risk of ecological change with climate change suggests that it would be prudent to put measures in place that enhance the resilience of rivers and their ecosystems to global warming. This is underscored by the inconvenient fact that current emissions policies at the global-scale are insufficient for limiting global warming to the 2.0°C goal of the Paris Agreement (Höhne et al., 2020), yet alone the 1.5°C goal. Moreover, current national emissions policies globally imply a global warming of between 2.6–3.1°C by 2100 (Rogelj et al., 2016), which is at the upper end of the warming scenarios considered in this study. Higher levels of warming were not considered because 3.0°C is the highest integer global-mean temperature rise projected by all five GCMs–less than 5 GCMs simulate warming of 4°C by 2100 under RCP8.5.

Although a number of conclusions have been drawn on the global-scale risks of ecological changes within rivers due to climate change-induced modifications to river flow, the study did not consider every basin across the globe. Basins were filtered by size and whether they were included in the GRDC database, meaning that approximately 50% of the Earth's land surface was covered by the study. The limitation of achieving full global coverage is common to all GHM studies where analyses are conducted across multiple basins (Veldkamp et al., 2018; Zhao et al., 2017). GHM grid-cell levels of risk (which could result in global coverage) were not assessed because the ERFA methodology was developed for basin or sub-basin scale analyses, and therefore applied as such. Furthermore, management practices and conservation efforts are better targeted at individual basins or groups of basins rather than at the scale of individual grid cells (in this study, approximately 50 × 50 km at the equator), so the study was conducted at the basin scale to help inform future management and conservation efforts. The basins provide a reasonable geographic coverage, but the filtering of basins resulted in the number of BOR and NML basins being proportionately high. Such biases in basin selection have been reported in previous studies (Zaherpour et al., 2018, 2019). Nevertheless, the basins are reasonably representative of the hydrobelts they are located within because for all but two hydrobelts (SDR and NDR) they cover at least 40% of each hydrobelt's total area and in the majority of cases over 50% of the area (Table 1). Recalculation of the number of basins within each hydrobelt with a total percentage risk score above the median of the 321 basins (i.e., Table S3 in Supporting Information S1) but after first normalizing the median using the number of basins in each hydrobelt shows that basin selection bias has no effect on the conclusions of the study.

ERFA, and other environmental flow methods that employ the RVA/IHA approach (e.g., Olden & Poff, 2003; Richter et al., 1996, 1997), are underpinned by the key controls that river flow exerts on ecological conditions and processes within riverine ecosystems. It is, however, important to recognize that river ecosystems are not only controlled by hydrological conditions (Laizé et al., 2017) so that there are other possible impacts of climate change on rivers that are not revealed using the approach employed herein. The most obvious direct impact is increased water temperate, which might in some instances outweigh the impacts of changing river flows (e.g., Oliveira et al., 2019), and lead to shifts in the distribution of species including fish (e.g., Comte & Grenouillet, 2013; Herrera-R et al., 2020). Other impacts might be expected in response to factors that include changes in concentrations of oxygen, nutrients and pollutants due to altered dilution and chemical reaction kinetics (e.g., Abily et al., 2021; Sjerps et al., 2017; Whitehead et al., 2009), and modifications to land use including agricultural responses to warmer temperatures and changing rainfall patterns (Thorslund et al., 2021). Lowland, estuarine rivers and their associated aquatic ecosystems are also likely to be subject to changes in saline intrusion due to sea level rise (e.g., Bellafiore et al., 2021; Bricheno et al., 2021). In common with the changes in river regimes revealed using ERFA in this study, these additional multifaceted impacts will vary regionally (e.g., Liu et al., 2020) adding to the complexity of assessing the implications of climate change on the world's rivers.

## 5. Conclusions

This study highlights the ecological fragility and spatial heterogeneity of the risks that unmitigated climate change poses to global rivers. The likelihood of different levels of risk (no risk, low, medium and high) were computed from a large ensemble of GCM-forced GHM simulations. Globally, climate change-induced modifications to both low and high flows present an increasing risk to river ecology with increasing global warming. Globally, the risks associated with low flows are greater than for high flows, reflecting larger increases in the frequency of low flow days and declines in low flow magnitude with global warming.

There is, however, spatial heterogeneity underlying the global-scale picture of increasing risk with climate change. Rivers in Boreal regions, that include the major northward flowing rivers of Siberia and North America, are least likely to see significant ecological change from climate-driven shifts in high and low flows. This must not be interpreted as no risk, or low risk, however, because the median of the total percentage risk score for the Boreal region is 48.9% at 3.0°C warming for low flows. The risk is lower than for other regions but by no means negligible. Furthermore, other non-riverine ecological impacts are expected in the high latitudes as a result of regional warming above the global mean, melting permafrost and shifts in vegetation. Southern dry and southern mid-latitude regions (exemplified by results for many rivers in South America, southern Africa and Australia) as well as northern mid-latitude regions (particularly in southern Europe and the central and eastern USA), are at most risk of experiencing significant ecological change due to changing river discharge, especially shifts in low flows.

The projections suggest that it would be prudent to put appropriate measures in place that enhance the resilience of rivers and their ecosystems to global warming and also balance human water consumption needs with ecological functioning, against a background of global warming that exceeds 2.0°C. In particular, climate adaptation mechanisms and mitigation strategies that pre-empt more frequent and drier periods of low flows could help with avoiding serious damage to river ecosystems in the future.

## Data Availability Statement

The datasets for this research are available via the UCL Research Data Depository: Thompson, J. R., Gosling, S. N., Zaherpour, J., and Laizé, C. L. R. (2021). ERFA risks of ecological change for global river flows. University College London. https://doi.org/10.5522/04/14134928.v1.

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