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Key Points:

- We assess how intensifying hydrological low and high extremes constrain renewable water resources globally under climate change
- We develop two metrics that quantify how changing hydrological extremes affect water availability for human use
- Projected declines in both metrics are widespread under climate change, while low-emission pathways can mitigate these declines

Supporting Information:

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

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Hydrological Extremes Increase Water-Resource Constraints Under Climate Change

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Abstract Hydrological extremes are projected to intensify under climate change, yet their implications for water scarcity remain poorly understood. We use a multi-model ensemble to assess how changes in hydrological low and high extremes will constrain renewable water for human use across 520 major river basins worldwide. We evaluate trends in two metrics of water availability: (a) annual lowest monthly runoff, and (b) annual accessible runoff, a conceptual indicator defined as total runoff excluding extreme high flows typically released rapidly for flood control. More than 40% of river basins are projected to experience declines in both metrics during 2015–2100. Mediterranean and several scattered basins are identified as hotspots where runoff reductions compound existing water scarcity. Scenario comparison shows that low emission mitigates, though do not fully eliminate, these declines, highlighting hydrological co-benefits of climate mitigation. The novelty lies in explicitly incorporating hydrological extremes into water availability assessment.

Plain Language Summary Climate change is expected to increase both floods and droughts.

However, we still do not fully understand how these changes will affect the amount of water that people can reliably use. In this study, we assess how projected changes in very dry and very wet conditions will influence accessible water across major river basins around the world. Our results show widespread declines in water availability, particularly in mid- and low-latitude regions. The Mediterranean and several other basins emerge as hotspots where future reductions may exacerbate existing water scarcity. Lower greenhouse gas emissions can reduce, though not fully eliminate, these declines, highlighting the water-related benefits of climate mitigation. These findings show that changes in hydrological extremes are likely to play an important role in shaping future global water resources and should be considered in water management and adaptation planning.

1. Introduction

Freshwater is fundamental to ecosystem health and societal development (Oki & Kanae, 2006; Vörösmarty et al., 2000), yet its scarcity increasingly poses threats to human well-being and sustainable development in many regions of the world (Huang et al., 2021; Liu et al., 2024). Both observational and modeling evidence, including river discharge records (Dai, 2016), in situ and satellite-based groundwater observations (Akl et al., 2025; Jasechko et al., 2024; Loaíciga & Doh, 2024), and hydrological simulations (Gosling & Arnell, 2016), consistently point to continued intensification of water scarcity worldwide (Greve et al., 2018; Ravinandrasana & Franzke, 2025; Schewe et al., 2014). It is estimated that about 4 billion people reside in regions experiencing water scarcity for at least one month per year (Mekonnen & Hoekstra, 2016), and exposure of the global population to water scarcity after accounting for water quality constraints is projected to rise to 56%–66% by the end of the century (Jones et al., 2024).

These assessments have been instrumental in diagnosing and projecting water stress (Gudmundsson et al., 2021; Mekonnen & Hoekstra, 2016), yet the implications of hydrological extremes for human accessible water remain less explicitly considered. Specifically, intensifying droughts reduce reliable water availability during dry periods (Liu et al., 2018; van Loon, 2015), whereas floodwater, which constitutes a high volume of total runoff, are often rapidly discharged to minimize flood risk (Samuels et al., 2008). Consequently, runoff occurring during extreme high flows may be less accessible for human use, consistent with the broader concept that not all physically available water is equally utilizable (Karimi et al., 2013). Previous water scarcity assessments mainly compare human water demand with seasonal or annual water availability (Liu et al., 2017), sometimes incorporating water-quality constraints (Jones et al., 2024; Ma et al., 2020; van Vliet et al., 2021).

Extensive evidence, including assessments from the Intergovernmental Panel on Climate Change (IPCC), has established that human-induced climate change is driving increases in extreme hydrological events such as droughts (Satoh et al., 2022; Shu et al., 2024) and floods (Gudmundsson et al., 2021; Milly et al., 2002), with widespread impacts on societies and ecosystems. The link between low-flow conditions and water scarcity is direct and well recognized, yet the role of floods in shaping scarcity remains less explored. Although warming may increase total annual runoff through an intensified hydrological cycling (Wang, Liu, Wang, & Liu, 2024), a larger fraction might occur as flood flows that are difficult to capture and utilize (Tang & Chen, 2025). Floods can also reduce human water accessibility by mobilizing pollutants and degrading water quality (Usman et al., 2026; van Vliet et al., 2023; Zou et al., 2023). Despite these clear shifts, the evolving hydrological regime, marked by more frequent and intense extremes (IPCC, 2022), is poorly represented in existing water scarcity frameworks.

In this study, we focus on the hydrological dimension of water scarcity by investigating the effects of hydrological extremes rather than future water demand, to provide a diagnosis for anticipating potential pressures on water resources even under stable demand conditions by the end of the century. Beyond the well-documented increase in extreme low flows and floods, our analysis adds an important dimension to global water scarcity research, in which both low- and high-flow extremes act as additional stressors that compound existing water scarcity under a warming climate.

2. Data and Methodology

2.1. Hydrological and Climate Modeling Data Under the ISIMIP3b Protocol

We used a multi-model ensemble approach to assess future changes in runoff during the future period (2015–2100), using the historic period (1985–2014) as a comparison reference. The analysis used outputs from coupled Global Hydrological Models (GHMs) and General Circulation Models (GCMs) developed under the Inter-Sectoral Impact Model Intercomparison Project phase 3b (ISIMIP3b) protocol (Warszawski et al., 2014), which applied the most up-to-date framework and used bias-corrected CMIP 6 climate forcings to capture future climate-impact uncertainties. GHMs are critical tools for diagnosing factors of changing hydrological trends (Bierkens, 2015). Hydrological simulation results were from three GHMs, that is, CWatM, H08, and MIROC-INTEG-Land, as they provide consistent outputs of both water availability and water use for water scarcity assessment. Each GHM was forced with bias-corrected climate data from five GCMs, including GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The model outputs were provided at a spatial resolution of $0.5^\circ \times 0.5^\circ$ with daily temporal resolution. Future simulations were provided under multiple Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), including SSP1-2.6, SSP3-7.0, and SSP5-8.5, capturing low-to very high-emission scenarios.

Model outputs of total runoff (including both surface and sub-surface runoff) and water uses from each GHM–GCM combination were aggregated to 520 major global river basins (GRDC, 2020) to derive ensemble medians and inter-model variability. These aggregated results were used to estimate annual lowest monthly runoff, annual accessible runoff (excluding hydrological high extremes from annual runoff), and water use for each river basin. The multi-model ensemble framework accounts for uncertainty in hydrological models and climate projections, providing a robust assessment of future water resources (Giuntoli et al., 2015; Satoh et al., 2022).

2.2. Two Metrics: Annual Lowest Monthly Runoff and Annual Accessible Runoff

To separate the hydrological dimension of water scarcity, we focus on renewable water availability and construct two metrics: (a) annual lowest monthly runoff, and (b) annual accessible runoff, defined as annual runoff with hydrological high extremes excluded. These two metrics capture the effects of low- and high-flow hydrological extremes on water availability and provide indicators for hydrological constraints on accessible water availability, completing conventional drought and water scarcity metrics. The annual lowest runoff is selected as an indicator of low-flow conditions because it represents the most constrained period of water availability within a year. Although floodwater can potentially contribute to groundwater recharge and reservoir replenishment, extreme high flows are often rapidly conveyed downstream and require substantial storage, regulation and treatment before they can be effectively used. This annual accessible runoff metric represents a conceptual indicator of human use accessibility rather than a direct estimate of usable water. Both metrics are calculated for major global river basins by aggregating runoff from model grids to basin-level totals.

A river-basin-level time series of annual lowest monthly runoff is constructed based on monthly hydrological simulations by extracting the lowest monthly runoff in each year. This metric captures the minimum monthly renewable water availability at an annual basis and characterizes basin-level hydrological low-flow conditions.

Annual accessible runoff time series is constructed by subtracting hydrological high flows from annual runoff for each major river basin. Basin-specific high-flow thresholds are defined as the 98th percentile daily runoff during the historical reference period (1985–2014). The fully daily runoff on days exceeding the 98th percentile threshold is excluded considering the practical challenges of utilizing water during extreme flood events, including safety risks, high sediment loads, and operational difficulties for water intake and reservoir management. A fixed historical threshold, rather than an evolving threshold with future runoff distributions, provides a consistent reference for quantifying changes in the absolute volume of runoff exceeding present-day high-flow conditions. Recognizing that the degree to which extreme high flows can be captured varies among river basins depending on storage infrastructure and regulation capacities, the universal threshold is a simplification and may overestimate inaccessible runoff in highly regulated basins while underestimating it in basins with limited storage and regulation capacity. The annual accessible runoff metric is intended as a conceptual measure of water availability that is potentially more accessible for human use. We also conduct a sensitivity analysis with a 95th percentile threshold to define high extremes.

The two metrics are evaluated under three scenarios, that is, the low-emission SSP1-2.6, the high-emission SSP3-7.0, and the very high-emission SSP5-8.5. In the main text, we focus on the SSP3-7.0 scenario, because it represents a strong climate-change signal while avoiding the most extreme forcing assumptions. Results for SSP1-2.6 and SSP5-8.5 emission scenarios are briefly discussed, with maps provided in the Supporting Information S1.

2.3. Trend Analysis Using Linear Regression

Long-term trends in annual time series of hydrological variables are assessed using ordinary least squares linear regression. For each basin-level time series, the hydrological variable Y_t (i.e., annual lowest monthly runoff or annual accessible runoff) was regressed against year t to estimate the direction and magnitude of change:

$Y_t = \beta t + \alpha + \varepsilon_t$ where β is the linear trend coefficient, α is the intercept, and ε_t represents the residual error. The sign of β indicates whether a hydrological metric shows an increasing or decreasing trend over the study period. Statistical significance of the estimated trends was evaluated using a two-tailed t -test at the 5% significance level.

2.4. Synthetic Mapping for Compound Water Resources Risks

To evaluate combined pressures on freshwater systems, we construct a synthetic mapping that integrates trends in projected runoff with current river basin-level water scarcity conditions. This analysis does not constitute a projection of future water scarcity, as future changes in water demand are not considered. Instead, the analysis identifies river basins where climate-driven reductions in the two runoff-based metrics may exacerbate present-day water scarcity pressures.

Water scarcity is quantified for each major river basin as the ratio of total water use to annual runoff (Liu et al., 2017; Sun et al., 2021). Mean annual scarcity during 2005–2014 is used to represent current scarcity condition. Basins with scarcity greater than 0.2 are classified as water-scarce (Hanasaki et al., 2018; Ma et al., 2020). This 0.2 threshold is a commonly used benchmark. At this level, water withdrawal begins to place increasing pressure on the balance between human water demands and environmental flow requirements.

Projected trends in annual lowest monthly runoff and the conceptual indicator of annual accessible runoff are combined with current water scarcity to identify river basins where reductions in accessible water availability coincide with existing water scarcity. Compound-risk categories are assigned based on the co-occurrence of runoff declines and water scarcity. Triple-stressor basins with simultaneous declines in both runoff metrics and current scarcity represent the highest risk category. The resulting categories are mapped to reveal global spatial patterns.

(a) Future trend of annual lowest monthly runoff under SSP3-7.0 scenario

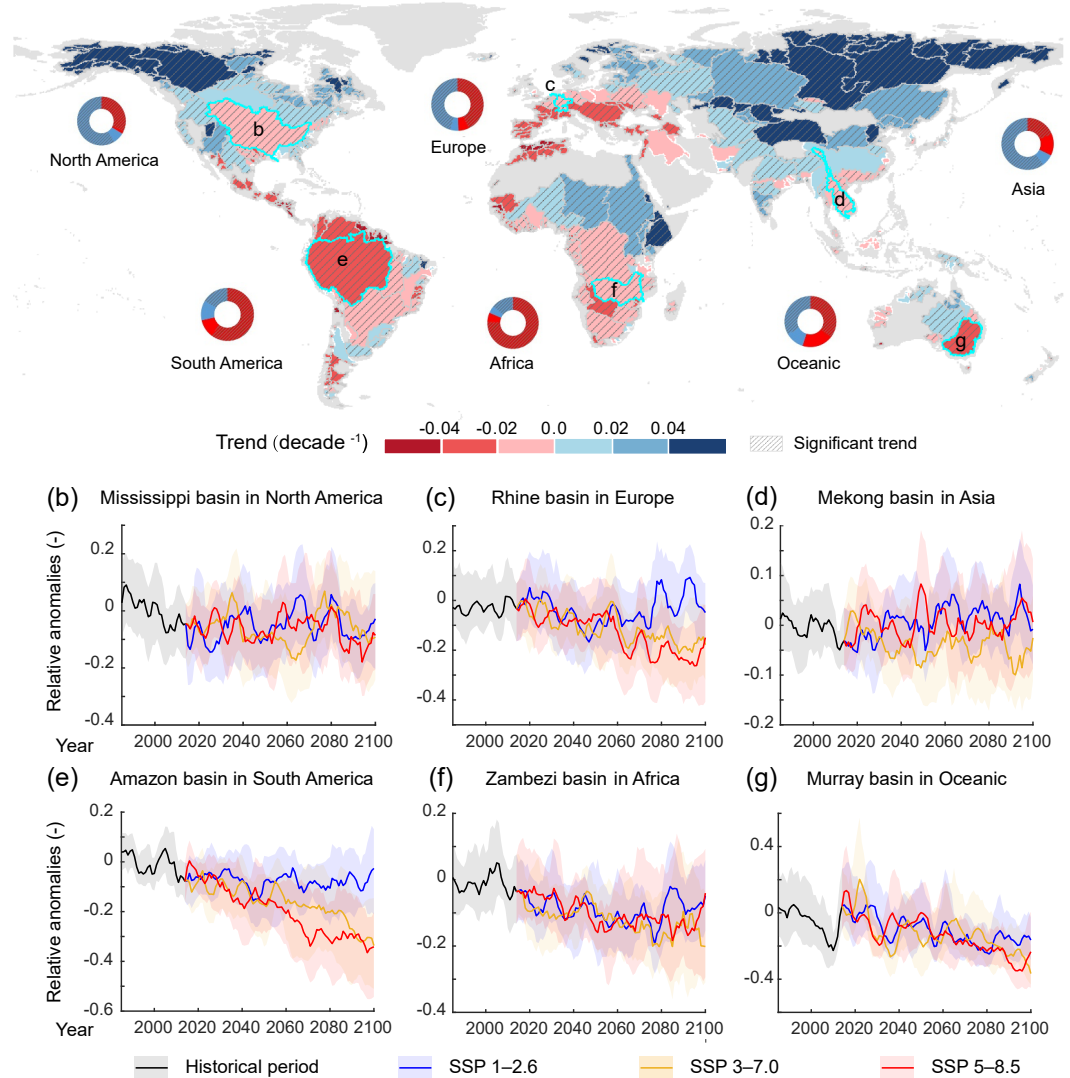


Figure 1. Projected trends in annual lowest monthly runoff across global river basins during future periods (2015–2100). (a) trends under the SSP3-7.0 scenario. Panels (b–g) show time series of relative anomalies in annual lowest monthly flows for selected river basins on different continents: (b) Mississippi River Basin in North America; (c) Rhine Basin in Europe; (d) Mekong Basin in Asia; (e) Amazon Basin in South America; (f) Zambezi Basin in Africa; and (g) Murray Basin in Oceania. Future trends shown in panel (a) are estimated using the linear regression incorporating 1985–2014 as the spin-up period. Trends with a p -value less than 0.05 are reported as significant. Gray areas indicate regions not mapped as global major river basins in the GRDC data set. In the pie charts, increasing and decreasing trends are represented in blue and red, respectively, and statistically significant trends are additionally marked by a hatch fill. In panels (b–g), the lines show the ensemble median time series for the three SSPs, and the shading shows the uncertainty represented by the interquartile range across ensemble members.

3. Results and Discussion

3.1. Trends in Annual Lowest Monthly Runoff

Projections from multi-model ensembles suggest that some river basins will face declines in annual lowest monthly runoff (Figure 1a). The global median trend in relative anomalies (i.e., deviations from the historical mean normalized by the historical mean) across all the river basins is a statistically insignificant $-0.002 \text{ decade}^{-1}$ by 2100 under SSP 3–7.0. Nevertheless, significant decreases and increases in trends are observed regionally. Among 520 global major river basins worldwide, 227 are projected to experience significant declines in annual lowest monthly runoff ($p < 0.05$). The decline is most pronounced in Africa and North America, where relative

anomalies of some river basins reach -0.05 decade⁻¹. These decreases in annual lowest monthly runoff are indicative of reduced baseflow and intensified dry-season low-flow conditions under a changing hydroclimatic regime, potentially exacerbating water scarcity pressures on human societies.

Projected trends in annual lowest monthly runoff show substantial spatial variation, which arises from global climate change mediated by local hydrological and land-atmosphere processes. At the continental level, Africa and South America are projected to face the most widespread declines, where more than three-fifths of river basins are projected to undergo significant downward trends. In Europe, significant decreases are evident across southern, western, central, and eastern regions, whereas high-latitude regions mostly display relatively stable trends with insignificant changes. North America displays a mixed pattern, with declines concentrated in the eastern United States and Central America, contrasted by increasing trends in high-latitude river basins. In Oceania, significant declining trends are primarily confined to the southeast region. Conversely, many river basins in Asia are projected to show significant increases.

Projected trends differ markedly among emission scenarios (Figure 1a and Figure S1 in Supporting Information S1). Ensemble simulations project significant declines in annual lowest monthly runoff for 129 and 224 river basins under SSP1-2.6 and SSP5-8.5, respectively. Representative river basins (Figures 1b–1g) show smaller reductions in annual lowest monthly under SSP1-2.6 than under SSP3-7.0 and SSP5-8.5, indicating the importance of pursuing a low-emission pathway (SSP1-2.6) to mitigate reductions in annual lowest monthly runoff.

Across all emission scenarios, decreases in annual lowest monthly runoff are projected in northern South America, Central America, parts of Mexico, the Mediterranean region of Europe and northern coastal North Africa, pointing to a persistent and intensifying dry-season water reduction. A total of 109 river basins show significant declines regardless of the climate pathway, indicating that some hydrological change may be unavoidable under ongoing warming, thus reinforcing the need for urgent adaptation planning. Nevertheless, many river basins avoid declines under the SSP1-2.6 (Figure S1a in Supporting Information S1), but face significant reductions under the very-higher-emission pathway SSP 5–8.5 (Figure S1b in Supporting Information S1). This clear mitigation signal shows that mitigation efforts remain critical to prevent the most widespread and severe hydrological stress.

3.2. Trends in the Conceptual Indicator of Annual Accessible Runoff

Multi-model ensemble projections indicate declining annual accessible runoff in 220 river basins under SSP3-7.0 (Figure 2a). Removing ephemeral flood peaks (high-flow extremes) allows us to focus on the baseflow and moderate runoff that constitute the more accessible portion of the water resources budget. Globally, under SSP3-7.0, increases in total runoff are widespread, but decreases are confined to regions where enhanced evapotranspiration driven by warming outpaces the intensification of precipitation (Figure S2 in Supporting Information S1). In total, 255 river basins show significant increases in annual runoff, compared with 146 showing significant declines. Regional contrasts are even greater for hydrological high-flow extremes, with 309 basins showing significant rising flood peaks and 100 showing significant decreases (Figure S2 in Supporting Information S1). When flood peaks are excluded from total annual runoff, significant declining trend in accessible runoff is most pronounced in a few river basins of North America and Africa (Figure 2a), where relative anomalies reached -0.05 decade⁻¹. This suggests that the intensification of the global hydrological cycle may amplify floods without proportionally increasing the low- and moderate-flow proportion of runoff in some river basins, which may complicate water management, in particular water retention for human water use, and increase water scarcity risks for human societies.

Projected trends in the conceptual indicator of annual accessible runoff display considerable regional differentiation but largely mirror spatial patterns of annual lowest monthly runoff, indicating widespread reductions in water availability during both low-flow periods and across the annual cycle. The highest proportions of river basins showing declining trends occur in Africa, South America, and Europe. Notable decreases are also projected to occur in Central America and Southeast Australia. In contrast, many high-latitude river basins across North America and Asia, display stable or positive trends, consistent with intensifying hydrological cycles and increased cold-season flows under a warmer climate. Although Asia has the lowest proportion of river basins projected with significant declines among all the continents, projected trends are heterogeneous, ranging from significant declines to increases among different basins.

(a) Future trend of annual accessible runoff under SSP3-7.0 scenario

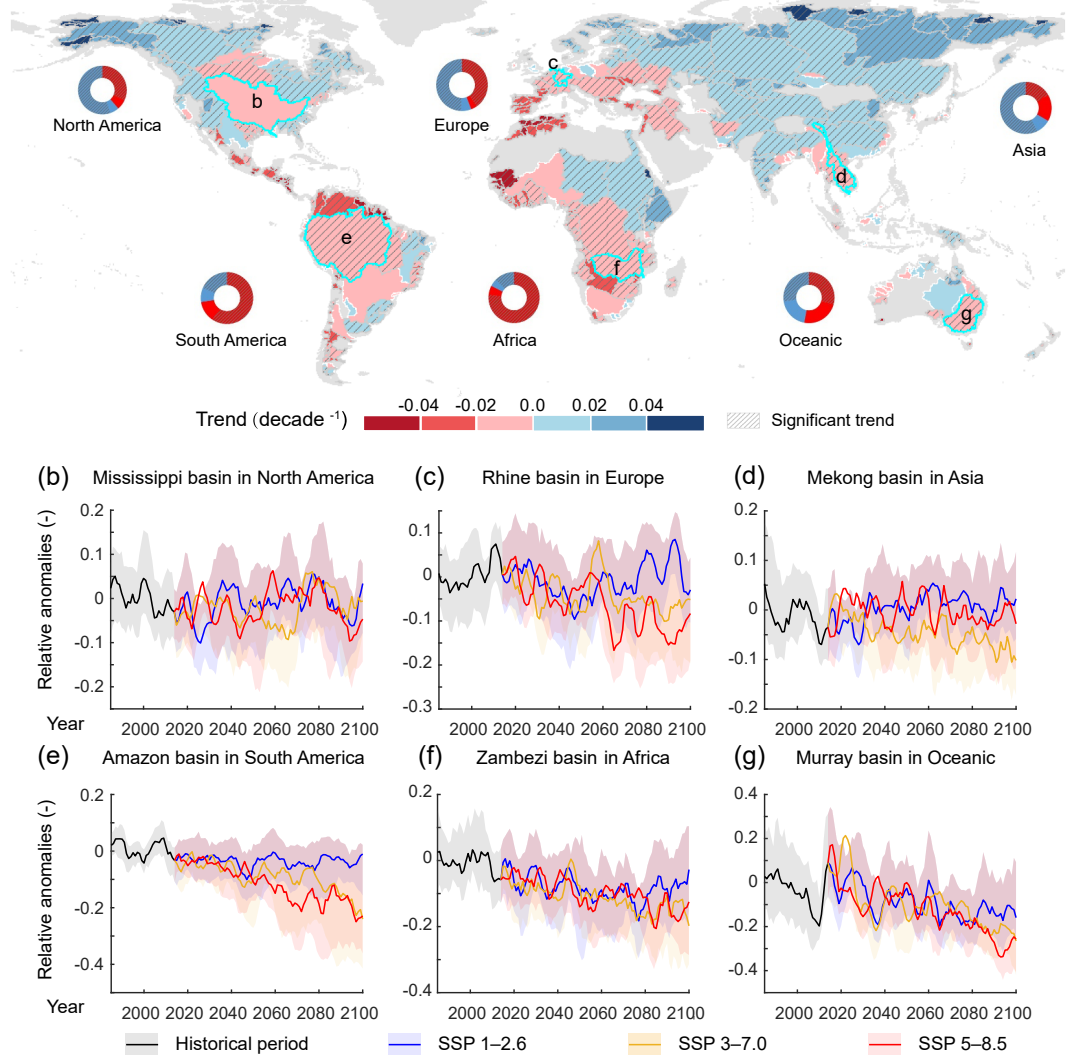


Figure 2. Trends in the conceptual indicator of annual accessible runoff across global river basins. (a) Trends during the future period under SSP3-7.0 (2015–2100). Panels (b–g) show time series of relative anomalies in annual accessible runoff for selected river basins on different continents: (b) Mississippi River Basin in North America; (c) Rhine Basin in Europe; (d) Mekong Basin in Asia; (e) Amazon Basin in South America; (f) Zambezi Basin in Africa; and (g) Murray Basin in Oceania. Future trends shown in panel (a) are estimated using the linear regression incorporating 1985–2014 as the spin-up period. Trends with a p -value less than 0.05 are reported as significant. Gray areas indicate regions not mapped as global major river basins in the GRDC data set. In the pie charts, increasing and decreasing trends are represented in blue and red, respectively, and statistically significant trends are additionally marked by a hatch fill. In panels (b–g), the lines show the ensemble median time series for the three SSPs, and the shading shows the uncertainty represented by the interquartile range across ensemble members.

The trend in runoff occurring outside extreme high-flow conditions is highly dependent on emission pathways (Figure 2a and Figure S3 in Supporting Information S1). Projections indicate that 105 river basins face significant declining trends under SSP1-2.6, compared to 207 under the fossil-fueled SSP5-8.5 scenario. Accordingly, the reductions under SSP1-2.6 are generally less severe than under SSP3-7.0 and SSP5-8.5 (Figures 2b–2g). Under the low-emission pathway (SSP1-2.6), more basins maintain stable accessible runoff, and projected declines are generally less severe, suggesting that climate mitigation is a crucial mechanism for managing future water resources.

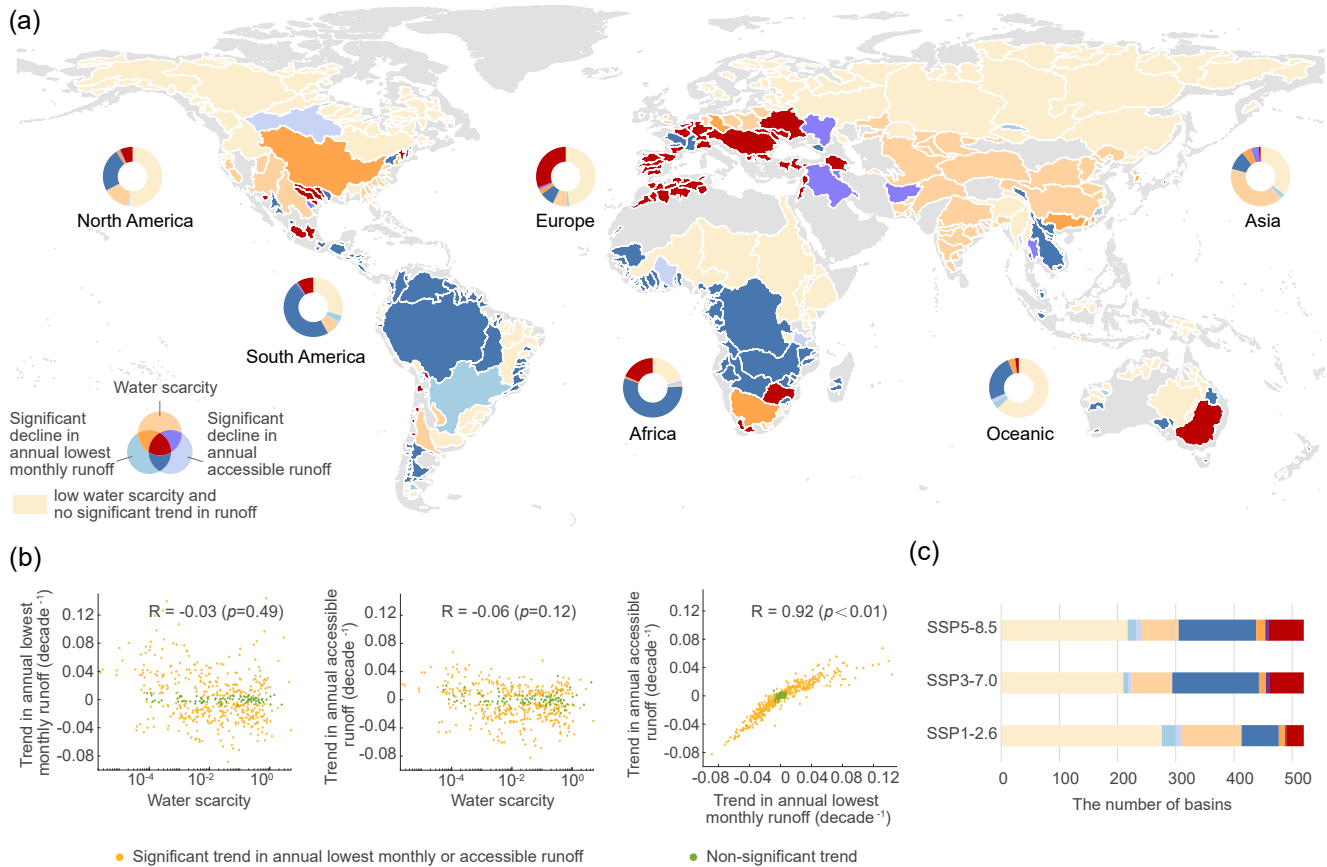


Figure 3. Compound water resources stresses on the global major river basins. (a) Spatial distribution of river basins classified by current water scarcity and projected trends in annual lowest monthly and the conceptual indicator of annual accessible runoff; (b) bivariate correlations; and (c) Number of river basins facing compound stresses under different emission scenarios. In panel (a), basins with scarcity value higher than 0.2 are classified as water scarce. The runoff trends are assessed under the SSP 3–7.0 scenario (2015–2100). Gray areas indicate regions not mapped as global major river basins in the GRDC data set. In panel (b), water scarcity and trends in annual lowest monthly and accessible runoff are not significantly correlated at the 5% significance level. Bar colors in panels (c) correspond to the bivariate categories shown in panel (a).

Across all emission scenarios, significant decreases in annual accessible runoff are projected in northern South America, Central America, the Mediterranean region of Europe, coastal North Africa, parts of coastal West Africa, and southeastern Australia, suggesting a future of persistently constrained annual-scale accessible water availability. Notably, 92 river basins face persistent significant declines across all emission pathways, locking in a future that requires urgent adaptation to hydrological shifts already underway. In the meantime, climate mitigation is equally important, because over 100 other basins are projected to avoid declines under SSP1-2.6, but experience significant reductions under high- and very-high- emission futures.

3.3. Water Scarcity Compounded With Changing Hydrological Extremes

The water scarcity assessment revealed that 147 out of 520 river basins, mainly located in densely populated regions across Asia, the western United States, coastal North Africa, Southern Europe, and parts of western Europe and eastern Europe, are currently facing water stress (Figure S4 in Supporting Information S1). This estimate of water scarcity, with the spatial resolution consistent with that of the hydrological trend analysis, represents a conservative assessment, as the annual and river basin-level analysis does not account for interannual or seasonal variability or sub-basin heterogeneity in water availability and demand.

The synthetic analysis reveals unequal distribution in future compound water resources stresses (Figure 3a). Under SSP 3–7.0, the highest-risk basins that are presently water-scarce and are projected to undergo future declines in both runoff metrics are concentrated in the Mediterranean region, with localized occurrences in southern Mexico, parts of Central America, the southern United States, parts of eastern Europe, southern Africa

and southeastern Australia. In contrast, some currently water-scarce regions, such as large parts of China and the western United States, have stable or increasing lowest monthly and accessible runoff, indicating limited added stress from future hydrological changes. Notably, some river basins in South America, central Africa and western Oceania that show no sign of water scarcity at present are projected to experience declines in annual lowest monthly runoff and/or annual accessible runoff. Conversely, high-latitude regions, including Northern Europe, Russia and Canada, will remain in a relatively secure state, showing neither water scarcity nor significant runoff declines.

While current water scarcity shows little correlation with future trends in runoff, declines in annual lowest monthly and the conceptual indicator of annual accessible runoff are highly spatially correlated (Figure 3b). This occurs because historical scarcity is mostly demand-driven, while future trends in runoff-based metrics are climate-forced. The synchronous decline in annual lowest monthly and accessible runoff means climate change may concurrently reduce baseflow and accessible water. This dual threat is consistent with the recent finding of spatially synchronized low and high hydroclimatic extremes (Wang & He, 2025).

Future compound water resource risks differ across emission pathways. The low-emission SSP 1–2.6 substantially reduces the spatial extent and severity of runoff declines compared to higher-emission scenarios (Figure 3c and Figure S5 in Supporting Information S1). Only a limited number of river basins, primarily in the Mediterranean and scattered elsewhere, are projected to face existing water scarcity compounded by future runoff declines. The number of these most water-stressed basins increases from 30 under SSP 1–2.6 to 58 under SSP 3–7.0 and 60 under SSP 5–8.5. Lower warming levels attenuate compound water resources stress, supporting the IPCC's finding that risks are increasing with every increment of warming and underscoring the need to integrate climate mitigation with adaptive water management (IPCC., 2023).

3.4. Discussion

In this analysis, we focus on changes in runoff to isolate the hydrological dimension of water scarcity. Building on earlier global assessments based on the ratio of water use to water availability, this approach quantifies how shifts in renewable water availability alone may impose constraints, independent of demand growth, which are highly uncertain under future climate scenarios (Greve et al., 2018; Liu et al., 2025). This water-availability-focused analysis provides a diagnostic basis for anticipating where water resources constraint is likely to worsen even under stable demand conditions. The analysis does not account for inter-basin water transfers, which may partially offset reductions in water availability in recipient basins and represent a potential adaptation strategy. Future research could integrate the metrics for hydrological constraints developed here with water use projections to evaluate their combined effects on future water scarcity.

Our trend analysis suggests a future with increasingly constrained low flows in a number of global major river basins. Previous studies attribute such declines to rising atmospheric evaporative demand under warming, which enhances evapotranspiration even in the absence of significant long-term changes in global precipitation and drought severity (IPCC, 2023; Vicente-Serrano et al., 2022). In contrast, modest increases in annual lowest monthly runoff at high latitudes may be related to changes in cold-region hydrologic processes, including intensified snowmelt and permafrost thaw, as reported in previous findings (Aygün et al., 2020; Wang, Liu, Klaar, et al., 2024). Meanwhile, non-climatic influences, such as land-cover change, may also exert controls on altering surface and subsurface hydrology (Haddeland et al., 2014; Zhou et al., 2023). This increasing low-flow trend in northern high latitudes represents a continuation of observed historic patterns (Wang, Liu, Klaar, et al., 2024).

We also project a declining trend in the conceptual indicator of annual accessible runoff across some low and mid-latitude river basins. Previous studies suggest that climate change intensifies the hydrological cycle and increasing precipitation extremes (IPCC, 2023; Konapala et al., 2020). Although increasing flood risks have been discussed much (Do et al., 2020; Hirabayashi et al., 2013), their implications for global water availability remain insufficiently explored. Despite an overall increase in total runoff in most global basins (Figure S2 in Supporting Information S1), a larger proportion is possibly being concentrated into high-flow events, leaving less baseflow and moderate flow accessible for human use.

We use the ensemble median of multiple GHM-GCM models to assess runoff trends, accounting for inter-model uncertainty (Liu et al., 2024; Satoh et al., 2022). In river basins where annual lowest monthly and accessible runoff show declining trends, the ensemble shows high consistency in the direction of change. Globally, 43.7%

and 42.3% of river basins are projected to experience significant decreases in annual lowest monthly and accessible runoff under SSP3-7.0, with more than 70% of them showing inter-model agreement among 12 or more of the 15 GHM-GCM combinations (Figures S6 and S7 in Supporting Information S1).

While this analysis draws on an ensemble of climate-hydrological model combinations, uncertainties remain due to limitations in hydrological model structure, process representation, and parameter extrapolation to future conditions, which are challenges shared by global climate-hydrology assessments (Gosling & Arnell, 2016; Greve et al., 2018). The three GHMs used provide consistent simulations of both water availability and water use, but structural model uncertainty and internal climate variability (e.g., El Niño–Southern Oscillation, the Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation) are not fully characterized and may influence the projected changes. Projections of precipitation and hydrological responses for extremes are more uncertain than for average events (Giuntoli et al., 2015; Schewe et al., 2019). Future research is needed to quantify the relative contributions of long-term climate change and internal climate variability.

The two proposed indicators involve subjective choices in defining extremes, and their trends may be sensitive to the selected thresholds. In particular, the annual accessible runoff metric is intended as a conceptual, globally consistent indicator based on a unified high-flow threshold, which may overstate or understate accessible water in individual basins. Nevertheless, the results are robust to alternative approaches: using a 95th instead of a 98th percentile threshold for flood-peak definition produces highly consistent trends ($r = 0.99$, Figure S8 in Supporting Information S1); and Mann-Kendall and Sen's slope analyses yield results consistent with Linear regression (Figure S9 in Supporting Information S1). The purpose of this study is to establish and demonstrate the relevance of incorporating hydrological extremes into accessible water availability assessment. These assessments are primarily intended to reveal water-resource constraints at global and large regional scales, rather than providing basin-specific diagnostic information. Future research should refine the representation of hydrological extremes and improve their simulation to better quantify their effects on constraining water resources.

4. Conclusions

Despite growing evidence of amplifying dry and wet extremes, their implications for accessible water resources remain insufficiently understood. This study develops two runoff-based metrics, that is, annual lowest monthly runoff and annual accessible runoff, to assess how low- and high-flow extremes constrain water availability. By explicitly accounting for hydrological constraints associated with both extremes, the analysis provides new insights beyond assessments based solely on annual or seasonal runoff totals. The annual accessible runoff metric should, however, be interpreted as a conceptual indicator because it relies on a simplified treatment of extreme high flows.

This study suggests a future with increasingly constrained low flows and annual accessible runoff in a number of global major river basins. The synthesis mapping identifies concerned river basins where compound water resource stresses emerge from the concurrence of existing water scarcity and projected declining runoff. In particular, under the SSP3-7.0 scenario, these hotspot regions include the Mediterranean, parts of western and eastern Europe and some scattered river basins across other continents. The emerging pressures in such regions signal a high likelihood of intensifying scarcity and growing management challenges under a warming climate. Beyond the well-documented increase in extreme droughts and floods (Asadieh & Krakauer, 2017; Roudier et al., 2016), this analysis adds an important dimension to global water scarcity research, in which both low- and high-flow extremes act as additional stressors that can exacerbate existing water deficits.

Despite uncertainties in simulating and projecting runoff at the basin scale, the ensemble-based results signify the necessity for mitigation and adaptation. The sensitivity of the conceptual indicator of accessible runoff to the degree of warming suggests that greenhouse gas mitigation can help reduce, but not eliminate, declines in water availability associated with intensified hydrological extremes. The projected reductions in low-flow and accessible runoff may increase challenges for water supply, irrigation, ecosystem protection, and other water-dependent activities, particularly in regions already experiencing water scarcity. Meanwhile, adaptation measures such as enhancing water storage and regulation capacity, and increasing water-use efficiency may become increasingly important for managing water resources under future climate conditions. Particular attention should be directed to mid-latitude river basins, where projected declines in the two runoff-based metrics coincide with existing water scarcity.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Historical and projected daily and monthly runoff data were obtained from multiple global hydrological models participating in the Inter-Sectoral Impact Model Intercomparison Project Phase 3b (ISIMIP3b), accessed through the publicly available ISIMIP data repository (<https://data.isimip.org/>).

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