Past and future change in global river flows

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Abstract

Rivers are a vital component of the global water cycle, and human influence on the climate and terrestrial systems is increasingly shaping their flow regimes. This review summarises the current understanding of past and projected changes in global river flow, focusing on annual volumes, seasonal dynamics and sudden changes. Observations reveal distinct regional trends, including increased flows in high-latitude regions and decreased flows in parts the mid-latitudes and subtropics. Especially snow dominated regions, also show shifts in their seasonal cycle towards earlier flows. These patterns align broadly with historical climate model simulations, suggesting an anthropogenic climate change signal. However, attribution is complicated by the interplay of greenhouse gas emissions, CO_2-driven vegetation response, land use change and water management. Future projections indicate continued change, with some regions experiencing wetter conditions and others intensified drying. Seasonal changes, particularly those due to altered snow dynamics, are also

expected to intensify. Despite modelling and observational advances, uncertainties regarding the combined effects of anthropogenic climate change and direct human interventions in terrestrial systems remain. Closing these gaps requires improved monitoring, advances in modelling and robust attribution frameworks, in support of efficiently managing water resources, sustaining ecosystems, and adapting to a changing climate.

Introduction

Rivers and streams are key components of the global water cycle, transporting approximately 46'000 km^3 of water from the land to the oceans each year, which corresponds to roughly 40% of all terrestrial precipitation[1-3]. River- and streamflow is the result of a cascade of processes that includes the storage of precipitation on land and its subsequent release back to the atmosphere as evapotranspiration or as runoff into the rivers. River flow is not only a response to atmospheric boundary conditions, but the dynamics of terrestrial water fluxes are modulated by processes that depend on factors including topography, soil texture or vegetation cover.

Humans are altering the Earth system at an unprecedented rate, affecting the global water cycle and thus river flow[1,4,5]. Human emissions are changing the composition of the atmosphere, and climate models project that global runoff will increase approximately by 3% for each degree °C of global warming[6], albeit distinct wetting and drying regions around the world[7-10]. Meanwhile, human water and land use can affect terrestrial water systems, either directly, through water withdrawals, reservoir construction and riverine engineering - or indirectly, by altering landscape properties that control the partitioning of incoming precipitation into evapotranspiration and runoff[1,11-13]. In total, human water use is estimated to amount to 24'000 km^3 per year[1,3], which is more than half of terrestrial discharge. Although appropriated water is usually returned to the system through processes such as irrigation, human water usage has an outsized role in the terrestrial component of the global water cycle.

Assessments of past[14-22] and future[23-28]changes in river flow indicate distinct regional responses to both anthropogenic climate change[7,12,18,29] as well as water and land use[12,30,31]. In many cases, however, the relationship between observed changes in river flow and anthropogenic drivers is less clear. Past and future changes in river flow have often been studied from differing disciplinary perspectives, resulting in a fragmented body of literature on river flow trends. Efforts to identify drivers at the global scale often focus on the effects of individual factors including e.g. water and land management[31-33] or the impacts of anthropogenic climate change[18,29,34]. However, study designs typically emphasizes the role of the focal driver, thereby complicating a comprehensive assessment while accounting for significant natural climate and environmental variability[35-37]. Moreover, there is a plethora of case studies that provide a detailed assessment of trends for individual river basins[38-41], but do not allow for generalizable conclusions.

This review aims at consolidating the knowledge on past and future changes in river flow, with emphasis on processes and phenomena that are relevant at continental to global scales. We focus on changes in annual mean and seasonal river flow, as changes in both wet[42,43] and dry[43] extremes have been addressed elsewhere. To consolidate existing knowledge on how human influence on the Earth system can affect river flow, a water balance perspective is taken to review mechanisms related to (i) anthropogenic climate change, (ii) the influence of elevated CO_2 on plant transpiration, (iii) land cover and land use change, and (iv) water management. Past changes are then presented, including trends annual flow magnitude, shifts in the seasonal cycle and abrupt changes in river flow dynamics. This backward perspective is mirrored by an assessment of how river flow is projected to change in a warming climate. The paper concludes with a synthesis of the key findings and highlights aspects of global river flow change that require further research.

River processes and human interactions

River flow is generated by combination of processes that determine the local terrestrial water balance and the lateral re-distribution of water along hillslopes and river networks[1,44,45] (Figure 1). In this context, the term

"local" indicates small land units that receive and store precipitation and then release water as both evapotranspiration to the atmosphere and as runoff to the river network. Different classes of processes – and hence also different drivers of change – control the local terrestrial water balance as well as the routing of water through the river network. Anthropogenic climate change, the impact of CO2 fertilization on plant transpiration, land use and land cover change primarily affect the local water balance. In contrasted water management can affect river flow both locally through impacts on runoff as well as regionally along the river network.

River flow processes

Local runoff is pragmatically defined as the gravity-driven flow of water above and below the land surface, that exceeds the capacity of land to absorb or retain water and often moves towards river channels. Runoff (R) is the residual of the local terrestrial water balance

$$R = P - E - dS/dt \quad (1)$$

that accounts for water input through precipitation (P), water loss through evapotranspiration (E) and changes in the amount of water stored over time (dS/dt). Water storage compartments include snow and ice, surface water bodies, soil moisture, ground water as well as water stored by plants. The dynamics of runoff and evapotranspiration are thus determined by the state of different water storage compartments and the drivers of evapotranspiration, which include besides precipitation net radiative energy and water vapor deficit. While runoff dynamics are driven by atmospheric boundary conditions, they are also modulated by land properties that include but are not limited to topography, the water holding capacity of soils and vegetation cover.

Runoff across landscapes converges to form and flow into rivers and streams. Flow along the river network follows a gravity-driven wave that is modulated by factors such as channel bathymetry, slope, and water retention in the floodplain, wetlands, lakes and artificial reservoirs. Rivers can either be replenished by or infiltrate the underlying groundwater[46,47]. It is estimated that 50-60% of the river reaches on Earth cease to flow at least one day per year[48,49]. While natural streamflow intermittence is most prevalent in semi-arid and arid regions, where it may occur even in large rivers, it is also widespread in smaller headwater streams across humid regions[50]. Eventually, water flowing in rivers is transported to the oceans or inland sinks.

Anthropogenic climate change

Human emissions of greenhouse gases and aerosols are modifying the composition of the atmosphere and thereby affect the Earth's radiation and energy budget, which is also referred to as radiative forcing[61,62]. The resulting changes in the climate system affect the global water cycle[3,8,51] and the cryosphere[52,53] with possible implications on global river flow. Human influence on the climate system can thus affect the local water balance and hence runoff and river flow through changes in precipitation, the atmospheric drivers of evapotranspiration and the impact of warming conditions on the cryosphere.

Global precipitation is expected to increase in response to anthropogenic climate change due to higher evaporation rates over the oceans and a greater water-holding capacity of warmer air[3,8]. However, cooling effects of aerosols, rapid adjustments to radiative forcing and observational uncertainties make it difficult to detect the increase in global precipitation in the observed record[3,8]. As precipitation is also modulated by large-scale atmospheric circulation, it is not changing uniformly across the globe with distinct wetting and drying regions that are detectable in the observed record and can be summarized along a latitudinal pattern[54-57]: Over the past decades, annual precipitation had the tendency to increase in the tropics and at high latitudes, while it decreases in mid-latitudes in response to human influence on the climate system. Similarly, climate models project that annual precipitation at high latitudes will likely continue to increase, while the middle latitudes and the tropics are expected to experience a combination of drying and wetting[8,58-60], albeit significant model-spread that is most pronounced in tropical regions[10].

Evapotranspiration has increased across the world during the past decades[8,61-63], likely in response to human influence on the climate system[8,62-64]. The change is driven by an increasing water-holding capacity of warmer air, changes in near-surface radiative energy and modulated soil moisture[8]. In densely populated regions available evidence suggests that past evapotranspiration trends may have been more strongly influenced by anthropogenic aerosol- than by greenhouse gas emissions[65]. An increase in future evapotranspiration is projected for a large fraction of the global land area[8,60,66,67] and with smaller differences across models compared to precipitation[10]. The difference of precipitation and evapotranspiration (P-E) averaged over multiple years is projected to increase in high-latitude regions, tropical Africa, and South Asia. A decline in P-E is projected for several regions, including Central America, tropical South America, the Mediterranean, and southern Africa[68-70].

Observed declines in global soil moisture are likely due to changes in precipitation and evapotranspiration resulting from anthropogenic climate change despite considerable uncertainty[71-74]. Past trends in soil moisture vary spatially, and regional trends differ across data products[7,71,75,76]. Climate models project decreasing global mean soil moisture and terrestrial water storage in a warming climate, albeit with strong regional differences and a dependence on soil depth in the direction and magnitude of change[8,72,77,78].

Both seasonal snow cover and mountain glacier mass have declined significantly over the past century[79-82], which can be attributed to increasing temperatures and anthropogenic climate change[83-86]. Climate models project a continued decrease in both seasonal snow cover and mountain glacier mass[79,81,87], which is particularly relevant for streamflow in high latitudes.

Influence of elevated CO_2 on plant transpiration

Beyond its role in driving global warming, increasing atmospheric CO_2 may also impact plant transpiration and thus the local water balance. Increasing atmospheric CO_2 implies a decreasing need of plants to open their stomata for photosynthesis, which in turn decreases transpiration[88]. However, increasing atmospheric CO_2 also fosters vegetation growth, higher biomass, and an increase in plant transpiration[88-90]. Over the past decades vegetation greenness has increased, likely due in part to CO_2 fertilization[91]. This greening has been related to increased evaporation[89,91,92] and to decreasing river flow in water-stressed climates[93]. Conversely, global scale analyses[90], confronting model estimates with observed changes in river flow[94] as well as future runoff projections[95] find only limited plant physiological effects of elevated atmospheric CO_2 concentrations and highlight large model uncertainty[95].

Land cover and land-use change

Humans have affected about three quarters of the global ice-free land area through a wide range of activities including the conversion of forests into farmland or urbanization[96,97] with potential implications for terrestrial water dynamics[1,98,99]. Land-cover and vegetation affect the rate at which water is transported to the atmosphere through both physiological and biophysical mechanisms. However, the net effect of vegetation on evapotranspiration and runoff is subject to discussion and may depend on the antecedent environmental and climate conditions[100-103]. Nonetheless, global-scale assessments indicate that increasing forest cover or leaf area index are associated with higher evapotranspiration rates[89,104,105]. Similarly, it was found that deforestation is associated with increasing river flow, which is more pronounced in water limited areas and less apparent in snow dominated climates[106]. Evidence suggests that the large-scale re-vegetation of the Loess Plateau[107] and increasing vegetation activity in the Mediterranean[108] is associated with decreasing runoff volumes.

Urban expansion and the expansion of impervious surfaces affects regional water balance by increasing runoff and thus river flow. Increasing urbanization is associated with increasing annual maximum flood extent[109] and increasing runoff volumes[103,110-112], with some evidence suggesting that the effects are larger for catchments that have a high urban fraction to begin with[113].

Water management

Water management can influence river flow through a variety of means, including withdrawals, the construction of reservoirs, water diversions[114], channelization, floodplain management or wetland drainage. Here, the focus is on the withdrawal of water and the construction of dams as two of the most prevalent and impactful methods.

Water is abstracted by humans from surface and groundwater predominantly for irrigation, as well as domestic and industrial water use[99,115,116]. After usage, withdrawn water can either re-infiltrate, be transferred to other river basins[117,118], re-fed into the river further downstream, or contribute to evapotranspiration. Abstractions from groundwater can result in declines in the water table, evapotranspiration and surface water availability[119,120] but may also have the opposite effect when the water is used for irrigation. Globally, irrigation accounts for about 70% of all water abstractions[116] and is still expanding[121]. The increases in surface soil moisture resulting from irrigation can result in increased evapotranspiration rates[116,122] and a reduction in water availability and regional river flow volumes[30,108]. Model-based studies estimate that water abstractions reduce global river discharge to the oceans and inland sinks in the order of 2-3%[32,99,123,124], albeit significant regional differences.

Reservoirs and dams play crucial roles in flood control, sustaining populations, hydropower generation, and irrigation. The number of dams steadily increased throughout the 20th century leading to a fragmentation of the global river network[125-128]. It is estimated that about half of the world's largest rivers are affected by dams[129] and are thus not free flowing[130]. Reservoirs and dams can alter the flow regime of downstream rivers [30,31,131-136]. The effect of reservoirs depends on the proportion of water retained within the upstream river network and operation schemes. It is estimated that reservoirs have led to a net reduction in flow volumes and dampening of the amplitude of the seasonal cycle[30,31]. The magnitude of the impact on streamflow depends on the size and purpose of individual reservoirs and regional water demand[31].

Past changes in global river flow

Human influence on river flow can vary substantially depending on the type of human intervention and the flow generating processes that are affected. These overlapping drivers can lead to various temporal alterations to streamflow as well as spatial footprints of change ranging in extents[137]. To synthesize knowledge on past changes in river flow and to identify knowledge gaps, a non-exhaustive typology of possible changes is adopted[137] (Figure 2).

The first and most studied category of change involves monotonic trends in flow magnitude, including changes in annual low mean or high flows (Figure 2a). An example of this is increasing annual discharge, which can be driven by increasing precipitation. The second category of change involves gradual changes in the (seasonal) amplitude of river flow (Figure 2b), which might occur in the case of regulation that aims to reduce the differences between the high and low flow seasons. The third category describes gradual shifts in the timing of the seasonal cycle, where the occurrence of low or high flow seasons is moved throughout the year (Figure 2c), for example in relation to earlier snow melt. Finally, abrupt changes, exemplified here by a breakpoint in both the mean and variance can occur (Figure 2d), which is often associated with sudden shifts in water management.

Past changes in river flow are assessed using *in-situ* observations from gauging stations. Although these are the most abundant observations of the terrestrial water cycle[138], the available set of stations was not built up as a systematic network and is as a consequence unevenly distributed around the world with a disproportional number of stations in large, perennial and more densely populated water sheds[139]. This placement bias is amplified by both declining monitoring networks[140] and latency in data mobilization, notably in developing

countries (Box 1). Although, it may be appealing to augment station-based data with re-analysis based global reconstructions of river flow, the trend for several water cycle components based on re-analysis can be unbalanced at the global scale[141] and non-homogeneous[142,143]. As a consequence, model-based trend estimates of both local runoff[76], river flow[16,21,144] and other terrestrial water variables[145] are uncertain and can even have opposing trend directions in some world regions[76], which is why they are not considered here (Box 1).

At the scale of individual streamflow gauging stations, observed trends can vary greatly between locations due to natural variability in the atmospheric drivers, highly variable terrestrial processes and in response to localized effects of water management[15,17,146,147]. In addition, statistical trend testing at individual locations lacks the power to identify weak but spatially consistent change patterns[148] such as the emerging effects of human influence on the climate system. However, when aggregating local trend estimates to regional scales, robust patterns of change emerge in the global observational record[17,18,22]. The following assessment therefore focuses on the dominant direction of changes in reference regions defined for the sixth Assessment Report for the Intergovernmental Panel on Climate Change (IPCC)[149] (Figure 3, Figure S1).

Due to the steadily evolving nature of the Earth system, trend estimates in river flow are sensitive to the selected start and end dates of the analysis[17,113,150], highlighting the role of natural decadal variability in the Earth system[14,151-153]. Acknowledging this variability, the following assessment focuses on developing a comprehensive picture of changes in river flow over the past decades. To this end, sources based on observations covering a time frame that ranges at least until the year 2010 are primarily considered. Findings from the literature are augmented with updated trend-analyses of in-situ observations from the Global Runoff Data Centre (GRDC), the African Database of Hydrometric Indices (ADHI)[154], a comprehensive streamflow collection for India (CAMELS-IND)[155], China[156], and Russia[157] using published methods[17,22] for the time period 1971-2020 where applicable (Supporting Information, Figure S2). Note, however, that that despite these data-mobilisation efforts the considered stations do not cover large parts of Africa and Asia, preventing an observational assessment in these regions.

Observed tends in annual river flow

Mean annual river flow is a key water availability indicator. Observed trends in annual river flow computed for the 1971-2020 time window reveal regions with predominantly increasing or decreasing river flow (Figure 3a,b, Table S3). In the northern high latitudes (NWN, NEN, CAN, NEU, RAR, WSB, RFE) and in parts of central Asia (ECA) as well as northern South America (NSA), river flow has significantly increased in 1971-2020. Significantly decreasing river flow is found in central Europe and the Mediterranean (WCE, MED), central South America (SAM, NES), the Indian sub-continent (SAS), East Asia (EAS), southern and eastern Australia (EAU) and New Zealand (NZ).

Previously documented global[14-17,19-21,158] and (sub-) continental[157,159-167] patterns of changes in river flow to balance spatial biases in the observational data (Figure 3c, Table S2, S3, Supporting Information). The considered studies are selected to include data until at least 2010. Since these studies do not provide access to quantitative information, the dominant direction of change for each region was determined visually from published maps (Supporting Information). Although this approach lacks quantitative rigor, it reflects the common practice not to provide quantitative trend estimates alongside the maps presented in publications. Given these caveats, this meta-analysis shows decreasing river flow in large parts of Asia (WCA, ECA, EAS) and the Sahara regions (SAH) with high consistency across sources.

In several regions the direction of assessed change in annual river flow differs between the trend assessment (Figure 3b) and the meta-analysis (Figure 3c). Reasons for these inconsistencies include but are not limited to differences in the considered time windows, differences in the considered stations, methodological differences across studies and inevitable uncertainties that arise when inferring dominant directions of change visually from maps. Instances in which both the regional trend analysis and the meta-analysis yield robust (respectively statistical significance and high agreement across sources) but opposing change directions

include NEN, NEU and ECA. In these regions the trend-assessment shows significantly increasing river flow, but the meta-analysis indicates no change.

Continental to global-scale patterns of change in past low, mean and high annual river flow are broadly captured by global hydrological models driven with atmospheric forcing data, even if local water use and land-use are not accounted for[18] and despite uncertainties in re-analysis based runoff trends (Box 1). Similarly, changes in flow volumes are correlated with changes in precipitation in more than two thirds of the world's largest rivers[158,168]. Overall, the above evidence suggests that changing atmospheric conditions (e.g. precipitation, factors affecting evapotranspiration) are dominant drivers of past changes in river flow volumes at continental to global scales, which is consistent with the finding that many managed and natural catchments react similarly to climate change[166].

As global-scale changes in river flow are linked to atmospheric conditions, the question arises whether human influence on the climate system is contributing to the observed pattern of change. Climate change detection and attribution techniques that combine observational and model-based evidence to distinguish emerging change patterns from internal climate variability are used for this purpose[51,169]. It has been shown that global and regional spatial change patterns in annual low[18], mean[18,21,34,170] and high[18] flows are consistent with climate model simulations that consider the effect of human emissions – including both greenhouse gases and aerosols – on the climate system and that observed spatial trend patterns cannot be explained by natural climate variability alone.

However, there are only few detection and attribution studies targeting changes in yearly mean river flow, and those that exist either focus either on the net anthropogenic forcing including greenhouse gas and aerosol emissions[34] or on total historical radiative forcing, which incorporates natural factors such as the influence of large volcanic eruptions[18]. Therefore, the available evidence does not permit a clear-cut distinction between the effects of the respective factors. However, consolidating knowledge of how human influence on the climate system and natural radiative forcing affect both precipitation and evapotranspiration provides additional insight. There is substantial evidence of the influence of greenhouse gas and aerosols forcing on large-scale changes in precipitation[8,51,55,171] and evapotranspiration[8,51,62,65] which are directly linked to runoff and river flow through the land water balance. Additionally, there is emerging evidence on the influence of global dimming and brightening in response to aerosol emissions on northern hemisphere river flow[172] and some evidence of a short-lived, yet globally distinct response of river flow to increased aerosols following large volcanic eruptions[173].

Many of the regions that are assessed to have declining river flow also coincide with regions of global irrigation expansion[116,121] and there is growing regional evidence that declining river flow may be aggravated by irrigation[108,174]. Overall, this spatial association highlights that water abstractions can contribute to the declining regional river flow, although the superimposition of climate driven drying and increased irrigation[121] hampers an unambiguous separation of both factors from a purely observational perspective. Model simulations indicate that water abstraction from irrigation may indeed lead to declining regional runoff, albeit significant uncertainties related to different irrigation parameterizations across models[12,99,175,176].

Observed trends in annual low and high flows

Changes in river flow extremes are often characterized by indicators for the days with the largest and the lowest flows, such as the annual minima or maxima as well as low (5^{th}) and high (95^{th}) percentiles. Annual low, mean and high river flow statistics have changed concurrently in several world regions over the past decades[17,18,166,177]. This similarity indicates that regional wetting and drying patterns can propagate to the magnitude of hydrological extremes, albeit some spatial variability at smaller scales. Regionally coherent trend patterns for low, mean and high flows are fore example found in North America[17,166], parts of south America[17,162], the Mediterranean[17,177] and southern Australia[17,178]. In other regions, however, trends in mean and extreme flows can be disconnected as illustrated by increasing annual mean flows and decreasing annual maximum flows in parts of Russia[157].

Observed trends in amplitude and phase of the seasonal cycle

River flow often has a pronounced seasonal cycle that is determined by precipitation, evapotranspiration and storage processes[22,29,131,179]. In cold regions, low flows are often associated with snow accumulation and high flows with snow melt[22,179,180]. In other regions, the low flow season is either associated with low precipitation or high evapotranspiration rates, whereas high flows often coincide with the dominant precipitation season[22,131,181,182]. At the global scale, evidence suggests an increasing number of locations with changing river flow seasonality[29] that are characterized by both changes in amplitude[131] and timing[22].

Declining seasonal amplitudes, characterized by decreasing differences between wet and dry-season river flow, are reported for many stations, although increasing seasonal amplitudes have also been found for some basins[131]. The tendency for declining seasonal amplitudes is most pronounced in the northern hemisphere and associated with changes in climate conditions, snow dynamics and water management[29,30,131,180], which is corroborated by seasonal trend analyses for several regions including Europe[177,183], Siberia [167] and New Zealand[184] that report increasing river flow in the cold-, and decreasing river flow in the warm season.

Changes in the phase – or the timing – of the seasonal cycle of river flow are often characterized by trends in the centre-timing (CT, also referred to as half flow date or centre of mass) metric that measures the day of the (hydrological) year at which half of the total annual discharge has occurred[22,180,185,186]. Reported changes[22] are complemented with a re-assessment the 1971-2020 time window (Figure 4 and Supporting Information). Shifts to significantly earlier river flow timing are observed for regions in the northern hemisphere (NWN, NEU, WCE) in which snow melt can have a strong contribution, although a deviation from this pattern occurs in NEN and CNA. The tendency towards earlier timing in snowy regions is consistent across global and hemispheric studies which conclude that increasing temperatures are associated with smaller snowfall fraction and earlier melting of snow and ice[22,180,187], albeit some heterogeneity in the response[188]. Similar conclusions have been reached in the U.S.[186,189-191], Canada[192-194], the Eurasian Arctic[161], and Europe[195-197], although reservoir operation can dominate downstream of large dams[132]. Formal detection and attribution work has demonstrated that changes streamflow timing in snowy climates are only consistent with climate model simulations that account for human influence on the climate system[29,186,189,193].

In other regions, changes in the timing of streamflow seasonality follow more complex spatial patterns that are usually linked to an interplay of shifts in precipitation, evapotranspiration and soil moisture[22,195,198]. In South America, a significant tendency to later timing is found for SAM and SWS, whereas NSA and SES show a significant trend towards earlier timing. In Africa the observations considered suggest a significant change to later streamflow timing ESAF. Observations from SAS show a trend towards later timing. Overall, rivers in Australia and New Zealand have a tendency towards earlier timing in that is significant in NAU, EAU and NZ.

Abrupt changes in past river flow

Time series of *in-situ* observations of river flow can exhibit abrupt changes, or breakpoints. Abrupt changes often occur in response to human interventions such as the construction of dams or the onset of water diversions but may also occur in response to natural disturbances like wildfires. Such abrupt changes are often characterized by shifts in either mean flow, the variability of flow or a combination of both. Overall, there is scarce systematic evidence of breakpoints in the global observational record[199]. It has been estimated that just below 20% of global river flow time series have strong evidence for a change point[199], although it is unclear to which extend this measure reflects gradual or sudden changes. Similarly, several assessments of the statistical homogeneity of observational time series report that more than 10% of available monthly streamflow time series may have abrupt changes in European[200] and global[179,201] data collections. Abrupt changes are often assessed in detail in case studies that focus on individual river systems in relation to the construction of dams[202-206], but such studies do not allow for a systematic evaluation of the occurrence of frequency breakpoints at the global scale. In addition, studies assessing large samples of river flow time

series globally[199], in the United States[207,208], Canada[209], Brazil[210] , Turkey[211], Mongolia[206] and Russia[157] report change points across stations that are often coherent in space and time. This alignment points towards common atmospheric drivers[199] and suggests that these may not represent abrupt changes but are rather expressions of decadal climate variability[14,151-153], leading to phenomena such as long drought episodes[163]. Moreover, it has been noted that many available tools lack the sensitivity to clearly distinguish step changes from trends[212].

Future changes in global river flow

Future projections of global river flow are based on Earth System Models (ESMs) that are used to simulate the evolution of the Earth's climate in response to emission scenarios[213,214]. ESMs compute runoff in their land-surface modules that consider vegetation dynamics, which can be fed into global routing models to derive river discharge[23,25,27]. A second approach are "offline" simulations that are based on using atmospheric variables from ESMs to drive dedicated global hydrological models (GHMs) or land surface models (LSMs) that compute both runoff and river flow[24,215-219]. To ensure consistent assessments, ESM projections are conducted in systematic experiments coordinated through the Coupled Model Intercomparison Project (CMIP)[220,221].

Similarly, the Intersectoral Impact Model Intercomparison Project (ISIMIP) coordinates standardized modelling experiments in which bias-adjusted[222] CMIP outputs are fed into GHMs or LSMs[28,215,217,218]. Any climate projection is prone to uncertainties related to internal climate variability (i.e. the irreducible natural variations of the climate system), model uncertainty and emission scenarios[223,224]. For runoff and related terrestrial water variables model uncertainty is dominating in most world regions[10]. The following sections focus on results derived from the fifth (CMIP5)[220] and sixth (CMIP6)[221] phases of CMIP and ISIMIP simulations based thereon[28,215,217,218] to ensure a timely assessment. Note, however, that literature pre-dating these efforts has yielded qualitatively consistent results[225,226].

Climate projections are typically communicated with a focus on representing the mean response of an ensemble of model simulations, alongside some measure of model agreement. This approach focusses on the expected climate response. However, it does not provide information on the expected range of possible future outcomes that are linked to internal climate variability and model uncertainties. Consequently, such representations are e.g. not indicative of risks related to physically plausible diverging but equally likely model trajectories[227], a factor that must be kept in mind for the following discussion.

Future changes annual river flow volume

Total global runoff is projected to increase in response to global warming but there are also significant regional and seasonal variations[7,8,60,228]. Spatially resolved projections of future grid-cell runoff derived from ESMs[8,59,60,229] and GHMs driven by ESM outputs[215,216] reveal systematic changes, albeit with significant uncertainties related to the choice of emissions scenarios, internal climate variability and the structure of the climate and hydrological models[10,60,215,224]. ESM uncertainty is found to be a dominating factor in CMIP6 based runoff projections, which is particularly pronounced in tropical regions[10]. Moreover, differences in the time periods used to quantify projected change hamper a comparison across studies.

Acknowledging these limitations, the focus of this assessment is on whether the considered ensembles suggest an overall increase or decrease in runoff and river flow in specific regions instead of a detailed quantification of the magnitude changes. Overall, the ensemble mean of 24 ESMs contributing to CMIP6 projects increasing runoff across roughly 70% of the global land area excluding Antarctica and Greenland[10,228]. This increase predominantly occurs in the high northern latitudes, east and south Asia and tropical Africa. Decreasing runoff is found in Central America, tropical South America, the Mediterranean and the southern tip of Africa, corresponding to approximately 30% of global land (excluding Greenland and Antarctica)[10,60,228].

Projections of future annual river flow in response to human emissions based on routing runoff rates from ESMs through the global river network[23,25,27,221,230] (Figure 5, supporting information for details) or by driving GHMs with atmospheric data from ESMs[24,28,216] and from multi-source assessments[7], reveal regions of increasing and decreasing river flow at the planetary scale in response to human influence on the climate system. Overall, projected changes in river flow follow local runoff rates but some features are propagated along the river network. World regions with model agreement for increasing river flow include the northern high latitudes (NWN, NEN, NEU, RAR), Asia (WSB, ESB, RFE, ECA, TIB, SAS, SEA), a small part of South America (SES) and central Africa (WAF, CAF, NEAF, SEAF). Drying regions, in which river flow is projected to decline, include Central America (NCA, SCA), large parts of South America (NSA, NWS, SAM, SWS, SSA) and the Mediterranean (MED).

Note, however, that significant differences can occur when comparing different model ensembles. For example, ensemble average changes of routed GCM runoff over tropical Africa and central Australia find increasing annual river flow[27,231], while changes derived from global hydrology models driven with bias-corrected GCM data suggest drying conditions[28,231]. Although the reason for such discrepancies remains to be explored in detail, it is interesting to note that projected water cycle changes in the tropics have been shown to be very sensitive to the considered GCMs[10] and that "offline" land-water projections based on processing GCM outputs can exacerbate drying[232,233].

Apart from the influence of anthropogenic emissions on the climate system, increasing human water use is also projected to affect terrestrial water systems and with potential implications river flow volumes in the future[115], especially in regions that are projected to see increasingly dry conditions[12] over the next century. In particular, irrigation is expected to increase globally[116], which may reduce regional runoff volumes[12,234,235]. This may reinforce hydrological droughts, on the Arab peninsula, parts of central Asia and the Indian sub-continent[236,237].

Future changes in annual low and high flows

Low, mean and high flows are projected to change concurrently across many regions around the world[27,28], reflecting similar observational findings[17,18,166,177]. Projections of annual low and high flows, respectively defined as the 5th and 95th percentile of daily river flows [27,28], broadly reflect changes in yearly mean flow (Figure 5), albeit some regional discrepancies that may also model uncertainties[27,28]. However, projected changes in return periods of annual maximum river flow suggest a different pattern: an increase in flood frequency in large parts of tropical Africa, tropical South America, south- and south-east and east Asia and a decrease in flood frequency in northern- and eastern Europe, central Asia and western Siberia[25,26,238]. Note, however, that decreases are mostly found for moderate floods, while there is growing evidence that the most extreme flood will also increase in Europe[239]

Future changes in seasonal river flow

Climate models project that runoff and thus river flows are not expected to change uniformly across the seasons in response to anthropogenic emissions in all world regions. The contrast is strongest between boreal winter (December, January, February) and summer (June, July, August) in northern high latitudes[8,10,59,228] (Figure 6), while other regions and seasons largely follow the change pattern of mean annual river flow (Figure 5). In boreal winter, pronounced runoff increases are projected in the mid northern latitudes and large parts of Asia with substantial agreement across the considered model ensemble, which is contrasted by markedly weaker signals and limited model agreement in the boreal summer, which may even see decreasing runoff in the northern high latitudes. This pattern is similar to projected changes in seasonal precipitation across northern mid- to high latitudes[8,59]. Moreover, this pattern is likely aggravated by projected increase in evapotranspiration[8] and decreasing seasonal snow cover[81], which has been associated with robust earlier peak runoff timing in snowy regions across the United States in response to global warming[240].

Summary and future perspectives

River flow is an essential component of the Earth system, driven by atmospheric supply and demand of water and modulated by terrestrial processes. Here, available information about past and future changes in global river flow was reviewed, with a focus on gradual changes in annual mean flow volumes and changes in seasonality. In addition, emerging evidence on the prevalence of sudden changes in past flow dynamics was considered. This review did not focus on floods and hydrological droughts, since they are covered extensively elsewhere[42,43,238,241]. Note nonetheless that low, mean and high flows have been observed to increase or decrease concurrently in many world regions[17,18,162,166,177,178,232] and are projected to continue doing so in the future[27,28].

Anthropogenic climate change, the effect of elevated CO_2 concentration on the biosphere, human interventions in the terrestrial environment and water management can affect river flow and there is evidence that all these factors play a role in changing river flow at the global scale. Emerging planetary-scale patterns of change in mean river flow and shifts in river flow seasonality in cold regions are linked to changes in atmospheric drivers and can likely be attributed to anthropogenic climate change. Although increasing CO_2 levels are affecting global vegetation and thus evapotranspiration rates, the net effects on global river flow remain subject to ongoing research. Model estimates indicate that large scale water abstractions (primarily for irrigation) reduce discharge to the oceans by 2-3%[32,99,123,124] and the global pattern of irrigated areas is correlated with past declines in river flow in several regions. Finally, reservoirs and dams can be associated with shifts in flow regimes although reductions of flow volumes have also been reported[30,31,131-136]. However, the strength of these effects is often largest in the vicinity of reservoirs and depends on the ratio of water being impounded relative to river flow.

Climate change vs. other human impacts on river flow

Advancing our understanding of the processes and drivers of river flow is essential for putting observed trends into context and for anticipating future changes. While this review highlights the extent of the accumulated evidence on past and future changes in global river flow, there remain pronounced knowledge gaps that need to be addressed considering an ever-increasing human imprint on the Earth system.

To date, few efforts have examined the combined impact of climate change, human land use, and water management on river flow at large scales[11,12,18,30,108,132,242-244]. Moreover, findings can be inconsistent, hinting at an unconsolidated understanding of how these factors interact. For example, warmer temperatures are changing snow dynamics and can thus alter the seasonal cycle of river flow at the continental scale[29]. On the other hand, in the vicinity of reservoirs, flow regulation can have a larger influence on river flow regimes than climate change in snow fed rivers[132]. Moreover, in regions with decreasing precipitation or increasing atmospheric evaporative demand, reduced water availability may be compensated by increased irrigation which may further accelerate drying[108,174]. These and similar examples highlight that our knowledge on the respective roles of anthropogenic climate change and direct human intervention in past and future changes in global river flow is not fully developed. This apparent gap poses significant limitations for anticipating and adapting to changes in river flow and emphasizes the need to further advance our understanding of changes in river flow and its drivers at regional to global scales.

Attributing observed changes in global river flow

Despite increasing knowledge of observed changes in river flow, systematic assessment of the key drivers remains scares at the global scale and are often focused on the treatment of isolated factors such as the impacts of reservoirs[30,31] or overarching effects of anthropogenic climate change[18,29]. To further advance our understanding of the most essential drivers of large-scale changes in hydrological systems, a consolidated

theory for attributing observed changes is needed, that rooted in physical understanding and accounts for both the large degree of natural climate and environmental variability as well as observational and model-structural uncertainty. This should be built on consolidating concepts of climate and climate-impact attribution[51,245], that are centred around explicitly formulated working hypothesis and a systematic integration of both observational and simulated evidence.

Attribution methods are centred around factorial simulation experiments that include and exclude the hypothesized driver of change and distinct assumptions of background variability. Attributing to anthropogenic climate change is based on ESM simulations with and without anthropogenic forcing, and attribution is claimed if the expected pattern of change derived from the model experiments is found in the observations given estimates of natural climate variability[51,169,245]. This can extend to systematically confronting ESM simulations with observed trends[246,247] while paying specific attention to regional inconsistencies between observations and simulations[248]. As internal climate variability may may mask emerging climate change signals at the station scale[35-37], targeting the emergence of regional to global scale change patterns can enhance signal to noise ratios[18,34]. Focusing on terrestrial processes, impact attribution protocols suggest to drive for example global hydrology models with raw and de-trended atmospheric variables to assess whether an observed change can be linked to trends in the respective atmospheric drivers[217]. Such setups could be extended to systematically test for the influence of landcover change and water management, for example by building on advances of modelling the effects of global irrigation expansions in ESM simulations[176,249].

Enhancing the observational basis

One of the major obstacles for detecting and understanding past changes in global river flow remains the limited accessibility of relevant observations for many regions[139]. Therefore, strengthening the observational basis is critical. Given that river flow remains the best-monitored variable of terrestrial hydro-systems[138,250], continued maintenance of observation networks[140] as well as mobilization and curation of available observations in international collections is essential. Apart from regularly emerging ad-hoc collections[20,201,251-253], continued support for the efforts of the GRDC that is mandated to collect and disseminate hydrological data under the auspices of the World Meteorological Organization (WMO) remains crucial. This effort should be augmented by data rescue initiatives for hydrological records, building on longstanding efforts in climate science to identify and digitize observational records[254,255].

Given that changes in river flow can be the result from both trends in atmospheric variables as well as from water and land-management augmenting available observations with relevant meta-information is essential. Examples include, reference hydrometric networks[253,256] that focus on compiling long high-quality records from relatively undisturbed catchments as well as calls for systematically collecting information on the degree of water management[135]. Moreover, so called naturalization methods aim at removing the influence of water management from observational time series, although the results can be uncertain and depend on the underlying assumptions[257].

Despite best efforts in data-mobilization, in-situ observations are spatially biased with incomplete temporal coverage and an under-representation of non-perennial rivers[20,139,201]. This incomplete spatiotemporal coverage highlights the need to maintain existing observatories and to expand the station network with a focus on locations that optimize information gain[139,258]. Records can furthermore be supplemented through estimates of past river flow at ungauged locations[259], for example by leveraging satellite monitoring of river discharge[260-262] or through coordinated ensemble modelling efforts[217,218,263], supplemented with operational reanalysis[264,265]. In addition, machine learning has shown promise to estimate runoff and river flow at regional to global scales[266-270], but challenges remain. These include but are not limited to extrapolating empirical

552 models to conditions not seen in calibration, developing compatible routing schemes, or accounting for water
553 management[271,272].

554

555 ***Consolidating model simulations***

556 Current literature on future changes on global runoff and river flow is spread over several communities that
557 operate from different points of departure. On the one hand, future projections of river flow can be based on
558 CMIP-style simulations[221] and rely on the increasingly refined land-surface components of ESMs that resolve
559 the coupled terrestrial water and energy balance with increasing capabilities to account for the carbon cycle,
560 landcover change and vegetation dynamics[273]. However, ESMs contributing to the CMIP efforts are mostly
561 run at low spatial resolution and do not account for human water management. Moreover, ESMs are often
562 biased and do not provide discharge along the global river network, which needs to be computed using
563 distinct routing models[23,25,26].

564 Simultaneously, efforts like ISIMIP[217,218] employ spatially downscaled bias-adjusted CMIP simulations to
565 drive GHMs that aim for detailed modelling of terrestrial hydrology, consider routing and direct human
566 interventions such as water withdrawals or dam operation[274-276]. However, ISIMIP has so far only considered
567 a reduced set of ESMs as inputs which might not be sufficient to cleanly isolate an emerging signal from
568 climate model uncertainty and internal variability. Moreover, bias adjustment can tamper with the climate
569 change signal as well as the physical consistency across variables[277,278]. In addition, many GHMs rely on ad-
570 hoc estimates of evapotranspiration that consider neither the surface energy balance nor plant physiology and
571 may respond too strongly to warming[233,279]. Finally, a lack of standardization for drainage direction maps
572 renders multi-model comparisons challenging[280].

573 So far, projections of future river flow based either on routing ESM runoff[23,25,27] or GHM simulations[24,28,216]
574 have often remained in their disciplinary silos and simulation experiments may not be directly comparable to
575 each other. Therefore, a closer exchange across modelling communities is essential to tackle the open
576 question whether differences in projections of future streamflow are due to model uncertainty, inclusion of
577 different processes, artifacts of bias correction or simply related to small ensemble-sizes that do not saturate
578 the distribution of internal climate variability.

579

580 ***Ecological and societal impacts of changes in river flow***

581 Changes in river flow affect the water level and extent of connected wetlands and lakes[281]. Reduction in flows
582 also affects the water and quality by increasing pollutant concentrations through reduced dilution volume[282],
583 which compounded with increasing water temperatures[283], affects both water supply and river biota. A
584 change in the river flow regime[284] translates into altered habitat availability and quality, influencing
585 ecological communities and their species composition. Aquatic ecosystems are sensitive to various
586 components of the flow regime and their variability. For example peak flows can lead to lateral floodplain
587 connectivity, dispersal and habitat complexity, while low flows can be particularly important for spawning
588 and recruitment of species[285].

589 Alterations of river flow causing dry periods are particularly disruptive for the river biota[286] and both
590 observational trends and future projections point towards drying in many world regions. Understanding of
591 impact of changes in river flow on river biota is complex and often limited by observations[287] or by
592 confounding factors in empirical analysis[287,288]. Yet, global scale studies predict that climate change will have
593 a negative impact on most species, for example ~36% of freshwater fish species seeing their range halved
594 under future climate[289].

595 Societies depending on ecosystem services from rivers are most vulnerable to impacts from altered changing
596 river flow and regime[290]. While impacts from changes in water supply for agriculture, industry, mining,
597 domestic water use, thermal and hydroelectric power generation[291], and shipping are most direct, impacts
598 from changes in water quality and temperature can also be important. Shifts in peak river flow timing and
599 increases in winter streamflow present opportunities for increased power generation, but conversely increased
600 dry days in the summer present power supply risks[291,292]. The boon of increased river flow, particularly in
601 tropical areas may improve agricultural production[293] but increased drought threatens yields[294,295] and may
602 create societal conflict due to migration to more arable areas[296].
603

Figure legends

Figure 1.

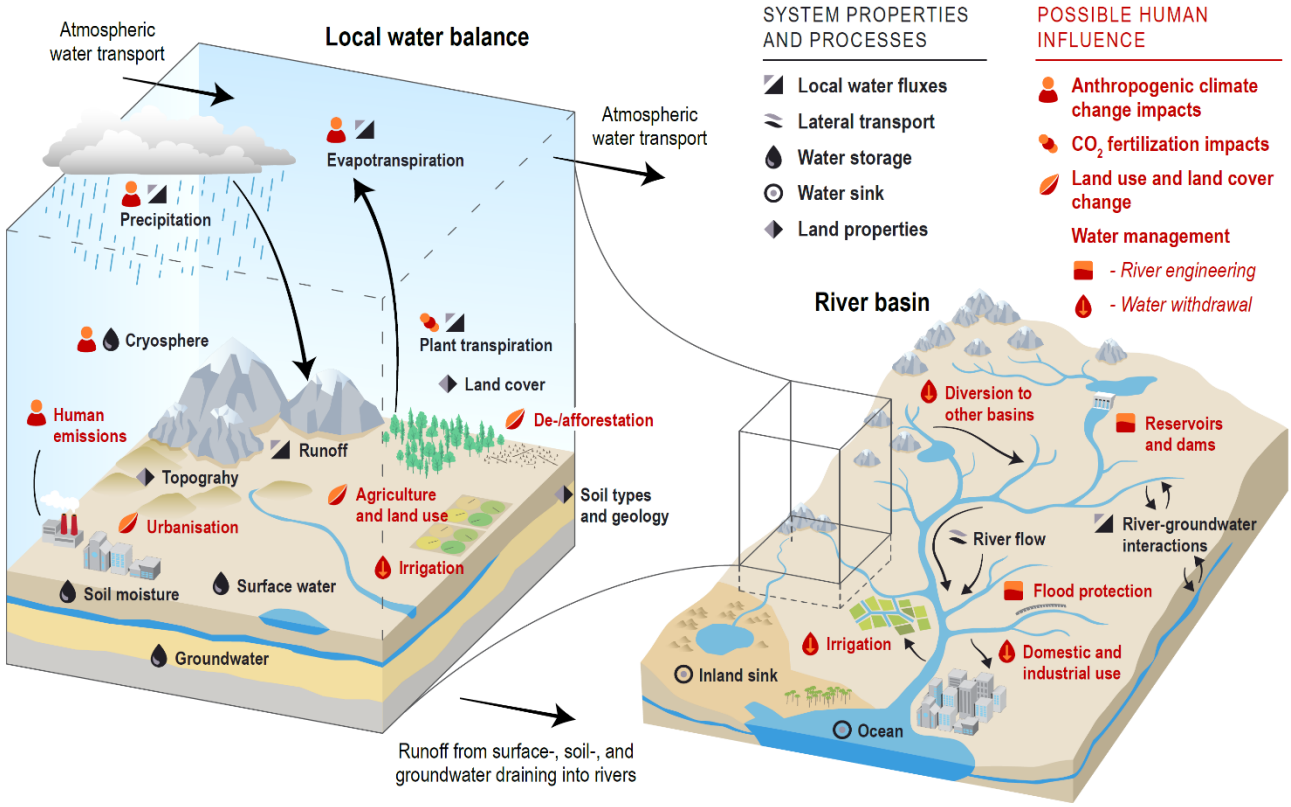


Figure 1. **Processes and drivers of river flow**. River flow originates from water-balance processes that determine how precipitation is partitioned into evapotranspiration, terrestrial water storage and runoff. These processes are driven by local atmospheric conditions and modulated by properties of the terrestrial system and local human activities. Runoff drains into rivers and is then routed along the global river systems to the oceans or inland sinks. The resulting river flow aggregates local runoff and in-channel flow is modulated by river-bed properties and human interference along the river channel. **[Figures will be edited by NREE]**

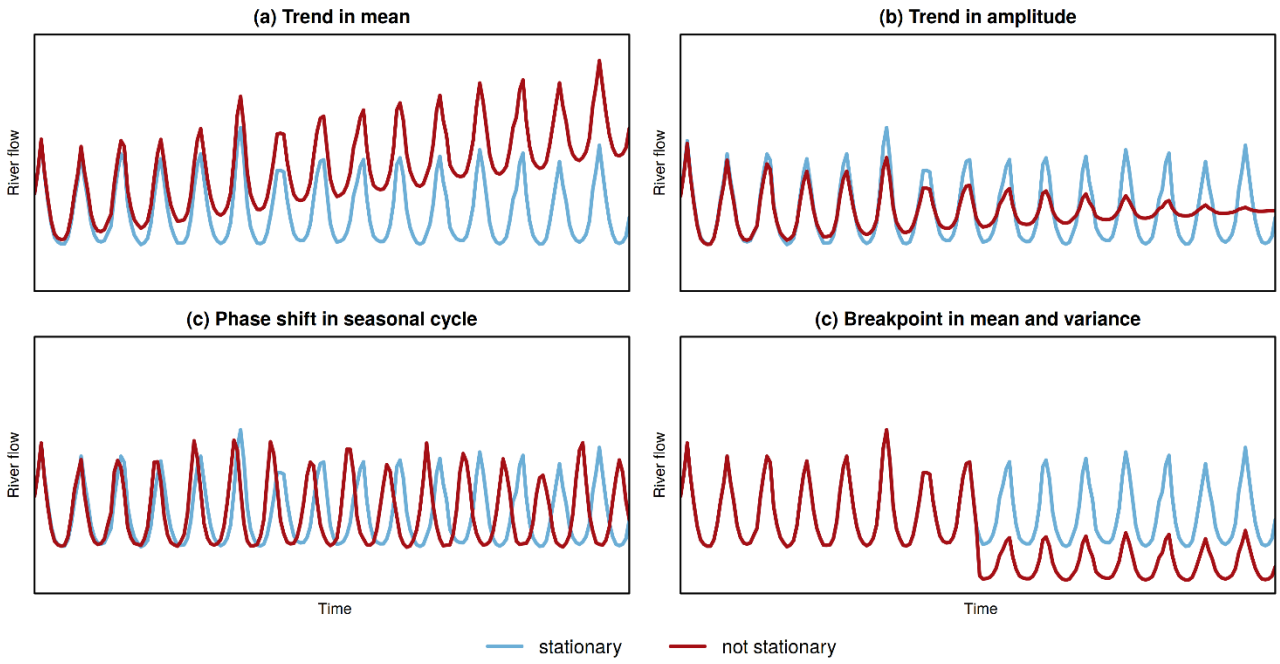


Figure 2. **A typology of changes in river flow**. Different processes can result in a multitude of changes in river flow dynamics. Illustrated here are (a) a gradual trend in the mean, (b) a gradual change in the amplitude of the seasonal cycle, (c) a gradual phase shift in the seasonal cycle, and (d) a sudden breakpoint in mean and variance. The changes illustrated are indicative of different categories but not exhaustive. Note that the different types of changes can coincide.

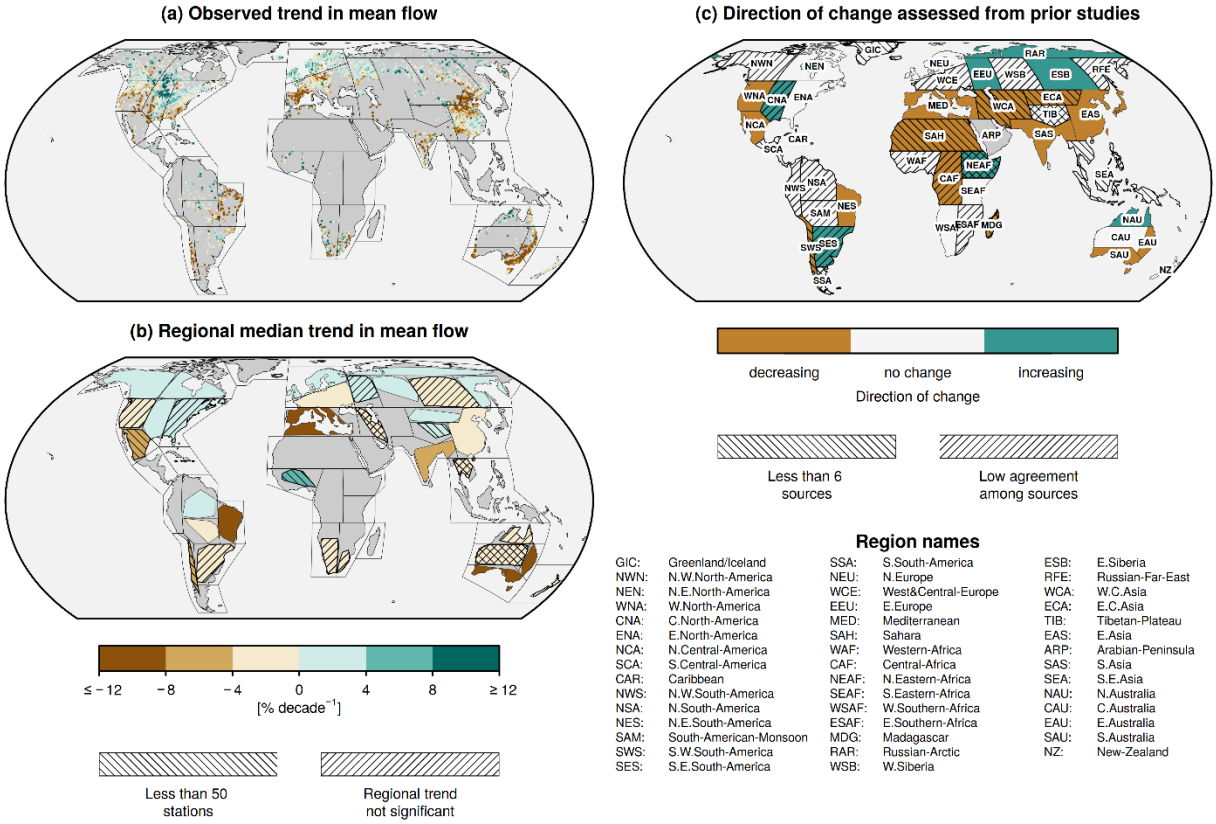


Figure 3. Past changes in river flow volumes over the past decades. (a) Observed trends in annual mean river flow for the period 1971-2020. (b) Regional median trends for regions with at least ten stations. Significance of the regional median trends is tested using bootstrapping[17]. Hatching indicates a non-significant trend (regional mean trend encapsulated in the 10-90% percentile interval of the bootstrap distribution) or regions with few stations. See supporting information for details. (c) Assessed direction of change in mean river flow is based on a synthesis of published large-scale studies that cover the year 2010 and report changes in river flow at continental to global scales(see supporting information). The set of considered publications are referred to as the number of sources. Note that the considered sources cover different timeframes and have different spatial extents and that all sources are weighted equally. The median record length is 40 years and the earliest and latest years considered are 1930 and 2022. Color-coding indicates the assessed direction of past change in river flow volumes. Hatching indicates either that only a few sources are considered, or low agreement among sources in the direction of change (low agreement among sources).

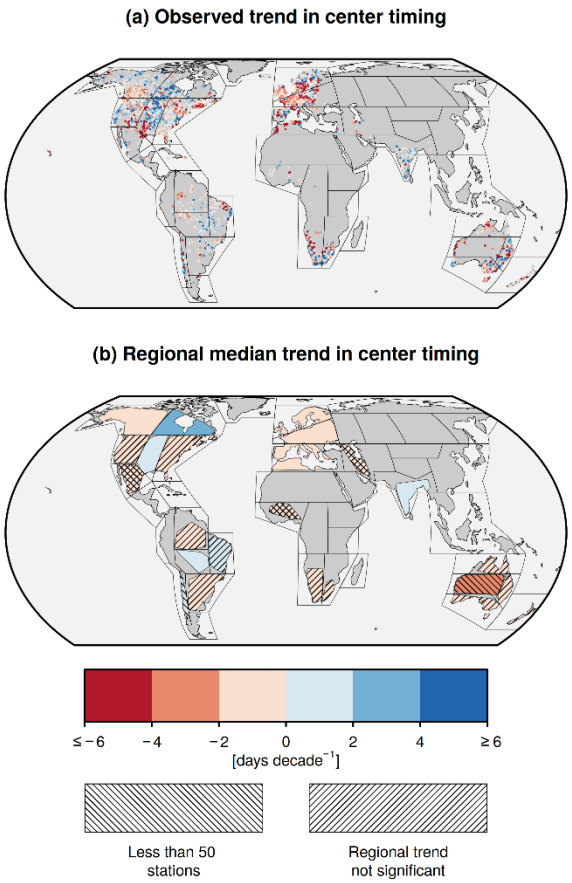


Figure 4. Observed trends in the timing of the seasonal cycle in river flow for the period 1971 - 2020. (a) Trends in the timing of the seasonal cycle are based on the center timing, defined as the day in the hydrological year by which half of the total annual flow has passed the gauge[22]. Trends in center timing are estimated using a robust estimator (Sen's slope) and expressed as days per decade, where negative values indicate an earlier timing. (b) Regional medians for regions with at least ten stations. Significance of the regional median trends is tested using a bootstrapping procedure[17]. Hatching indicates non-significant trend (regional mean trend encapsulated in the 10-90% percentile interval of the bootstrap distribution) or regions with few stations. Data from China and Russia where only available in yearly or monthly resolution and could not be considered here. See supporting information for details.

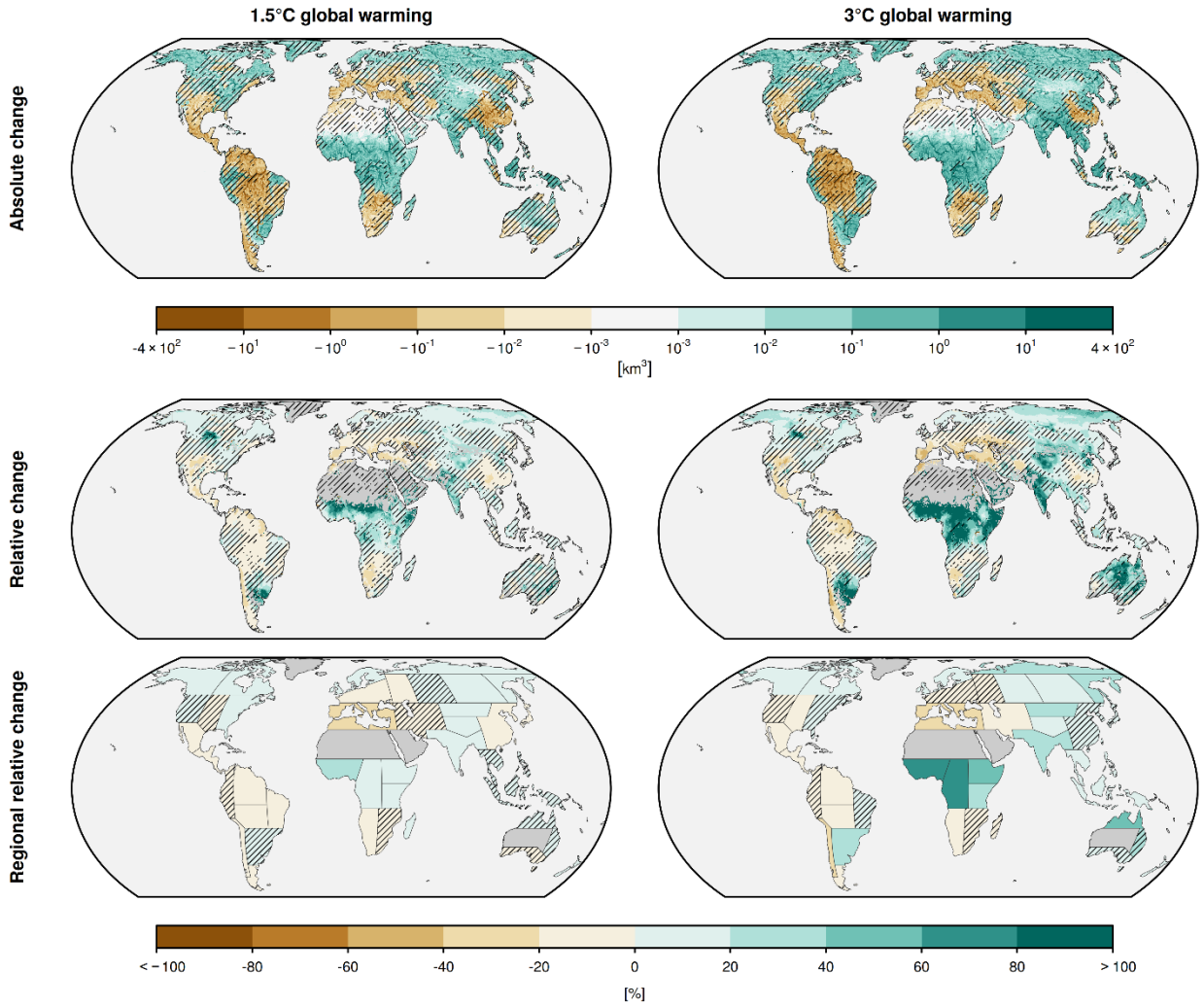


Figure 5. Future change in annual mean global river flow for 1.5°C and 3°C global warming, relative to the 1850-1900 mean. Simulations follow a previous assessment[25] that routes runoff from historical and future simulations from eight ESMs through the CaMa-Flood model[230] (see supporting information). ESM simulations originate from the CMIP6 archive[221] and assume historical radiative forcing until 2014 and radiative forcing following ssp585 thereafter. Ensemble mean changes are shown for degrees of global warming with respect to the pre-industrial mean (1850-1900)[60,297]. Relative changes are computed by dividing the absolute changes through the model-specific grid-cell mean from the base period. In this case, grid-cells with close to zero runoff in the base period are masked out prior to computing relative change to avoid unstable values related to zero division. Regions dominated by ice caps or extremely arid regions are left blank. Hatching indicates grid-cells and regions where fewer than six out of eight ensemble members agree on the direction of change. The analysis highlights that anthropogenic global warming is projected to alter river flow around the world, where some regions are expected to see increasing and others decreasing flow volumes.

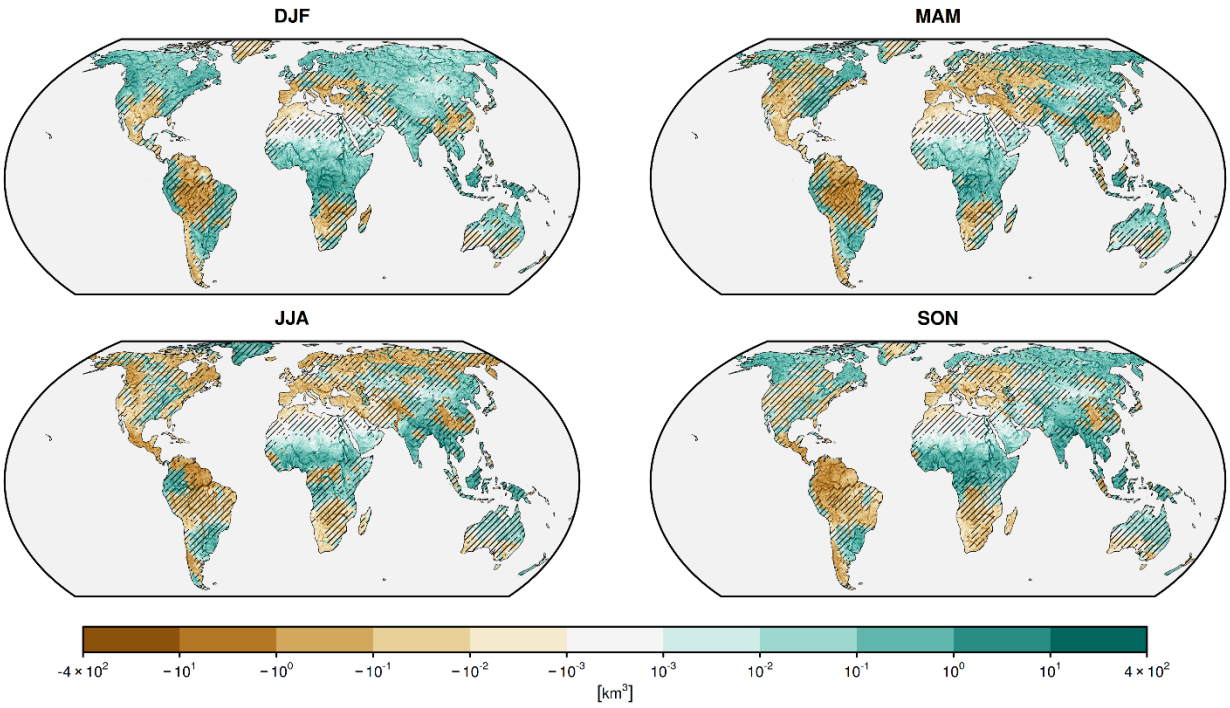


Figure 6. Future change in seasonal mean river flow for 3°C global warming, relative to the 1850-1900 mean. The underlying data are identical to Figure 5, but evaluated for the mean over December, January, February (DJF), March, April May (MAM), June, July, August (JJA) and September, October, November (SON). Hatching indicates grid-cells and regions where fewer than six out of eight ensemble members agree on the direction of change. Note the seasonal contrast between boreal winter (DJF) and summer (JJA).

Box 1 | **Data for quantifying changes past river flow**

In-situ observations: River flow is the component of the terrestrial part of the water cycle that is best monitored by in-situ observations[138,250], with a greater abundance of stations covering longer time periods compared to soil-moisture[298] or evapotranspiration[299]. The Global Runoff Data Center (GRDC) holds a large collection of daily river flow time-series around the globe. However, while the GRDC collection has been updated lately in the Americas, Europe, southern Africa and Australasia, there are fewer stations with up-to-date coverage in large parts of Africa and Asia. Despite efforts to combine regional data sources into global collections[20,201,251-253], the uneven spatial and temporal coverage of available observations[139] together with a decline of monitoring network in several world regions[140] remains a key limitation when assessing global changes in river flow. To mitigate spatial biases in station coverage, GRDC data are supplemented with daily river flow observations contributing to the African Database of Hydrometric Indices (ADHI)[154] in support of Figures 3 & 4 as well as a re-computation of previously published trends in annual mean river flow in China[156] and Russia[157] in support of Figure 3 (See also the supplement and Figure S2).

Model based reconstructions of river flow: Model based reconstructions or re-analysis of runoff and river flow with global coverage allow for insights into past changes at locations not covered by in-situ observations[300]. These reconstructions rely on physically-based[218,263,264,301-304] or data-driven models[14,179,269] that predict runoff and sometimes river flow as a function of gridded precipitation, temperature and other atmospheric drivers with global coverage[141,305-307]. However, water cycle estimates from atmospheric re-analysis can suffer from apparent inhomogeneities[142,143], which may cause spurious trends[308]. Moreover, uncertainty of gridded atmospheric data propagates through runoff and river flow models[144,259,309] and it has been shown that runoff is particularly sensitive to uncertain precipitation estimates[309]. As a result, river flow trends from re-analysis can exhibit systematic errors that depend on the atmospheric inputs[16,21,144] and runoff trends from different re-analysis based products can differ even in the direction of change for some regions[76]. Therefore river-flow trends from model-based reconstructions need to be interpreted with caution and are not considered here. Note, however, that regional trends in some reanalysis products do correspond to observational trends if modelled data are masked to match observational coverage[18,21].

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Competing interests
The authors declare no competing interests

Author contributions
LG set the scope and drafted the article with input from MB, PD, EFC, NF, SNG, YH, MK, DM, HMS, LSl, LSt, YT, CW, DY, XZ. LG analysed data and created figures. EF and CW contributed code for data analysis and visualization. YH, DY, XZ provided global river flow projections using the CaMa-Flood model. EFC post-processed global river flow projections. MK ran scripts to compute trends for Russian data, NF and DM provided updates and data analyses for Russia.YT provided updated data for Africa. XL and KW provided data analysis for China. All co-authors contributed with references and edits to the text.

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